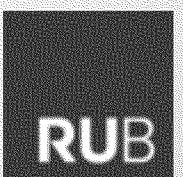
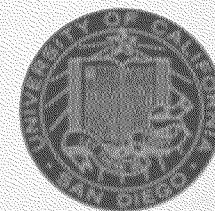


How They Did It: An Analysis of Emission Defeat Devices in Modern Automobiles

Kirill Levchenko

and

Moritz Contag, Guo Li, Andre Pawlowski, Felix Domke,
Stefan Savage and Thorsten Holz





VW's Costs Keep Adding Up From Its Worst Crisis Ever

By **Christoph Rauwald**

February 24, 2017, 10:25 AM PST

Updated on February 24, 2017, 12:53 PM PST

- Profit before some items rose 14% on sales, cost cuts in 2016

- Profit before some items rose 14% on sales, cost cuts in 2016
- Carmaker became world's biggest last year despite scandal

Volkswagen AG's provisions for the diesel-cheating scandal euros (\$23.9 billion), as the German carmaker continues to take the worst crisis in its history.

The company took a charge of 4.4 billion euros in the fourth quarter, double the total from the previous nine months, to reflect a tainted larger diesel engines and a criminal plea in the U.S. About that amount, the company's operating profit before special items increased 14% to 11.3 billion euros.

How They Did It: An Analysis of Emission Defeat Devices in Modern Automobiles

Moritz Contag[†], Guo Li[†], Andre Pawlowski[†], Felix Domke[‡],
Kirill Levchenko[†], Thorsten Holz[†], and Stefan Savage[†]

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[‡] tmbinc@elitedvb.net

- ❖ We're computer scientists, not diesel engine experts
- ❖ But at the heart of scandal is a *software system!*
- ❖ Our quest: figure out how they did it
 - No public details about the defeat device
 - What made this possible?
- ❖ ***How do we prevent this from happening again?***

Overview

- ❖ Diesel emissions
- ❖ Electronic engine control
- ❖ Volkswagen/Audi defeat device
- ❖ Fiat 500X diesel defeat device
- ❖ What next?

Diesel Emissions

- ❖ Combustion initiated by compression
(not spark as in gasoline engines)
- ❖ More soot (particulate matter)
- ❖ More NOx (NO and NO₂)

Emissions Standards

PM (g/kWh)

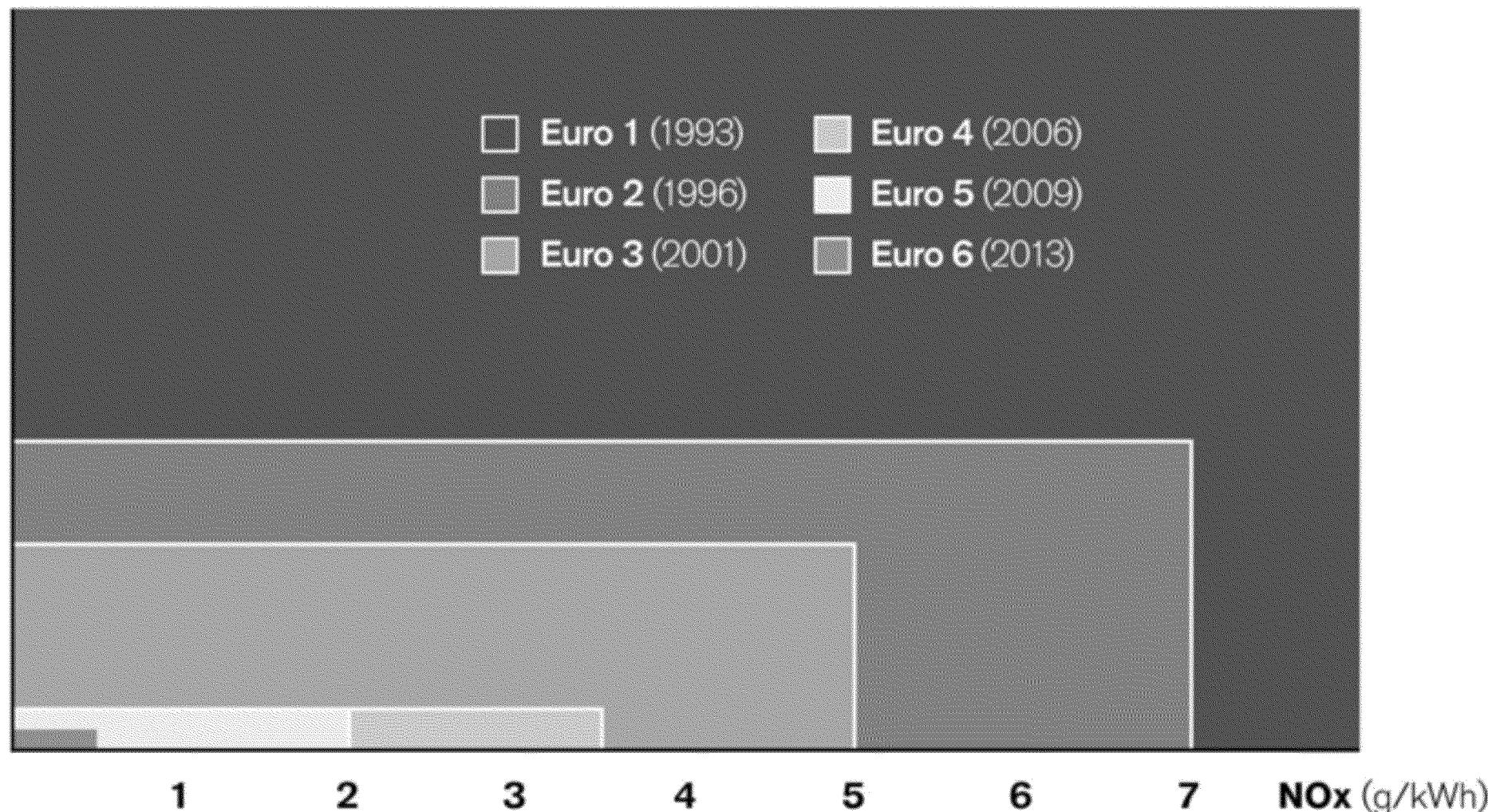
0,36

0,30

0,20

0,10

- Euro 1 (1993)
- Euro 2 (1996)
- Euro 3 (2001)
- Euro 4 (2006)
- Euro 5 (2009)
- Euro 6 (2013)



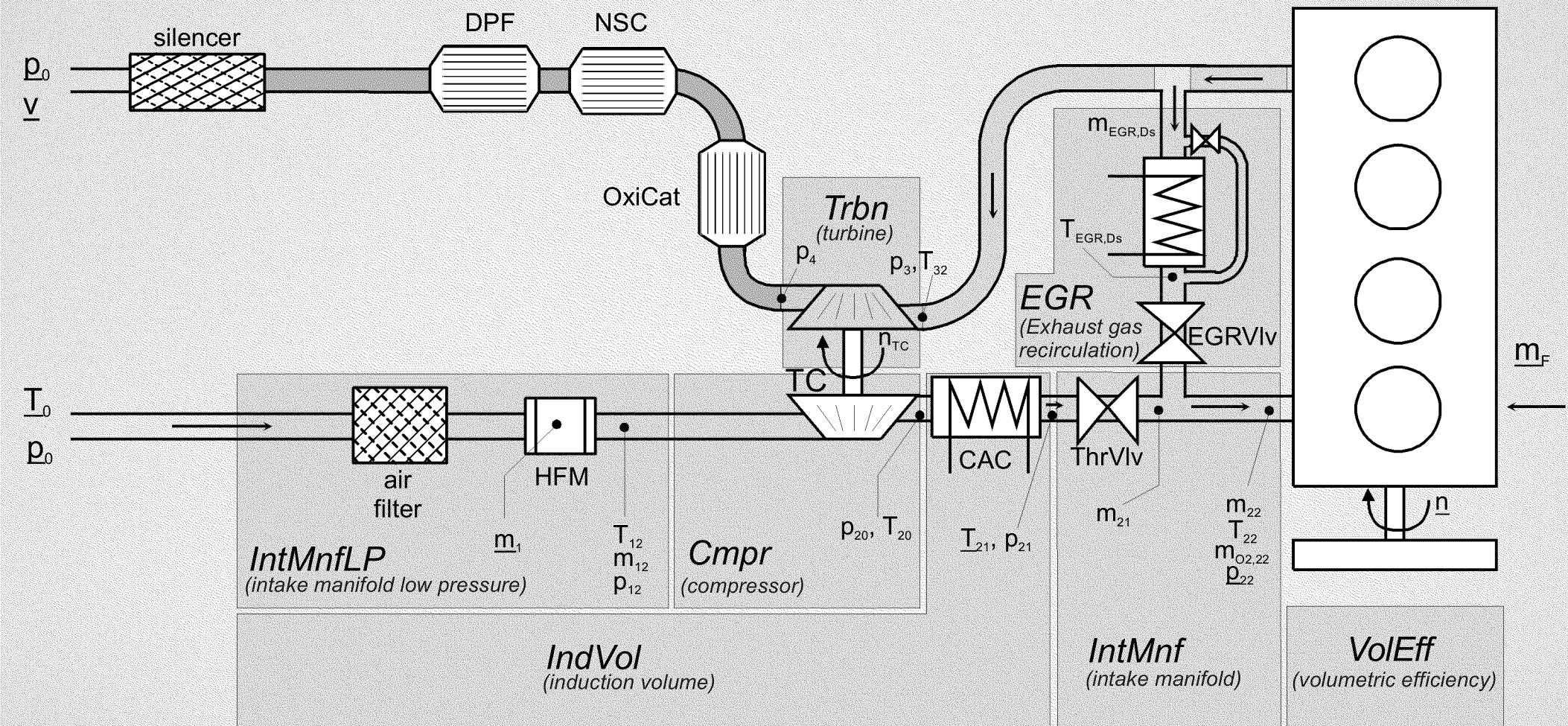


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Reducing Emissions

- ❖ Inside the engine
 - Fuel injection timing
 - Exhaust Gas Recirculation (EGR)
- ❖ Exhaust after-treatment
 - Diesel Oxidation Catalyst
 - NOx Storage Catalyst (NSC) a.k.a. Lean NOx Trap (LNT)
 - Selective Catalytic Reduction (SCR)
 - Diesel Particulate Filter (DPF)

Reducing Emissions

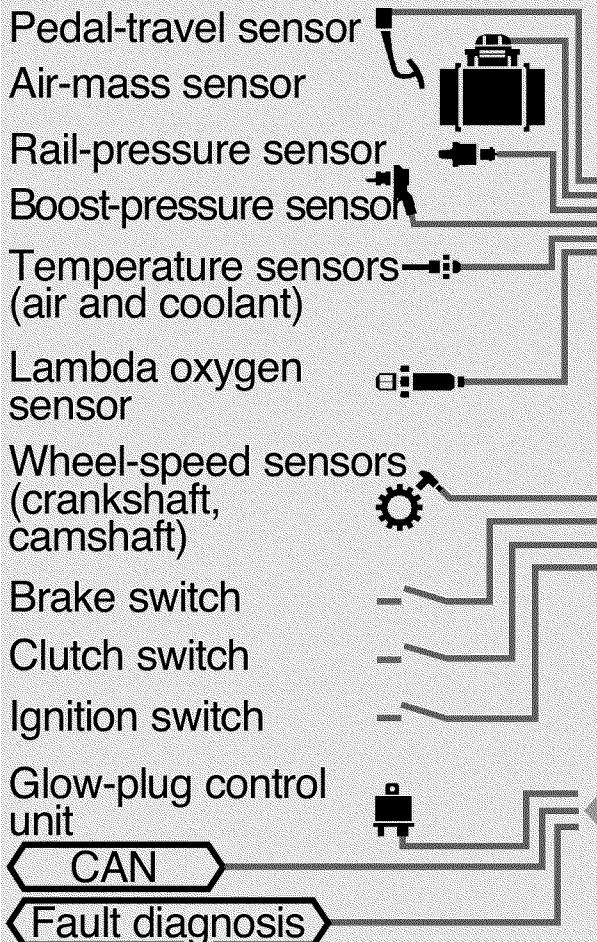


(source: EDC17C69 P1264 function sheet © Robert Bosch GmbH, dated 2013-10-21)

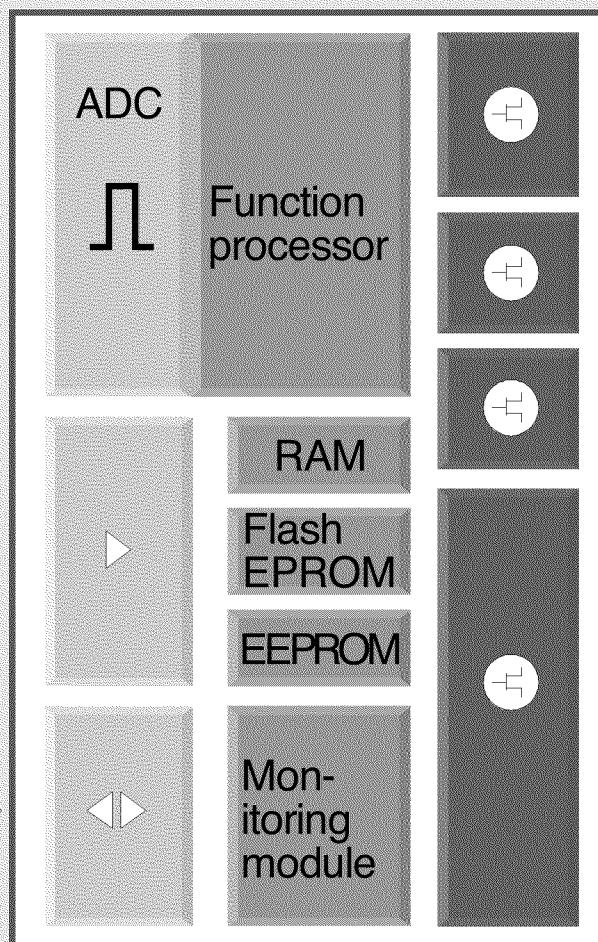
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Electronic Engine Control

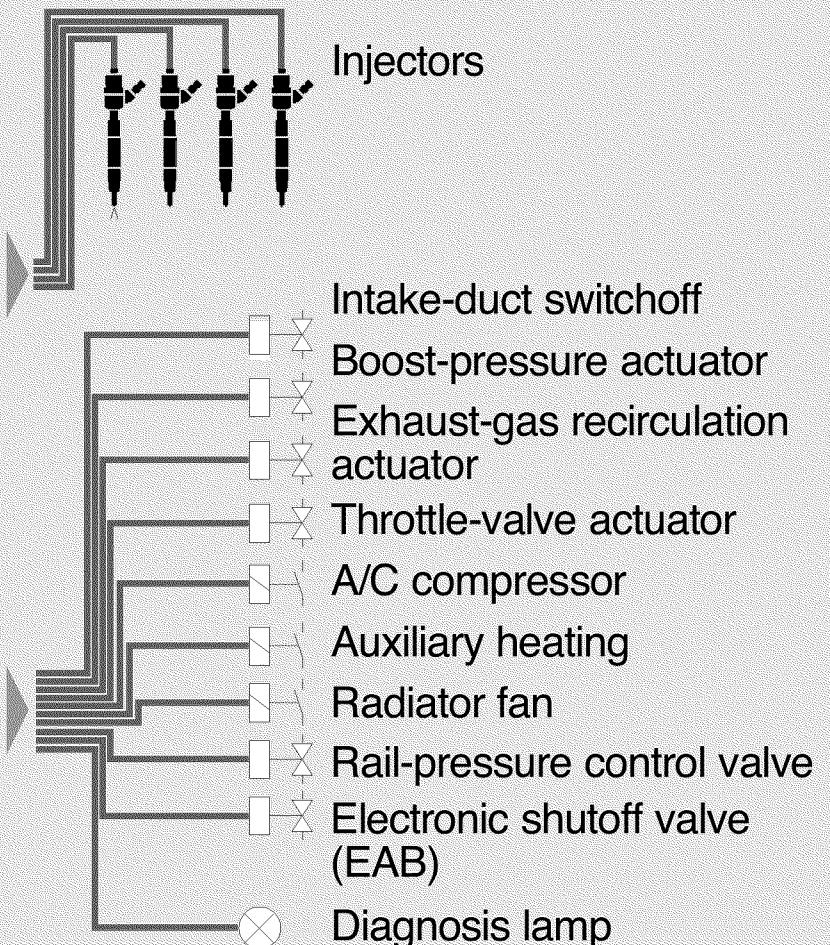
Sensors and setpoint generators



ECU

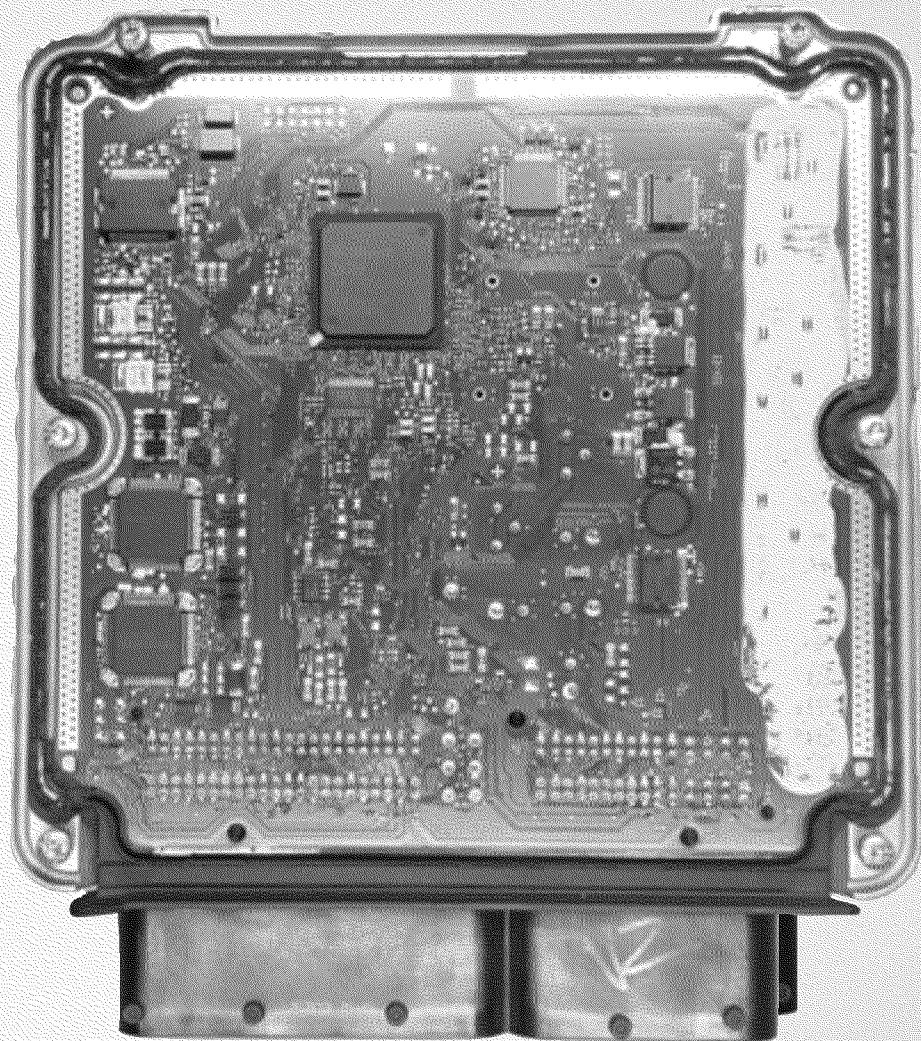


Actuators

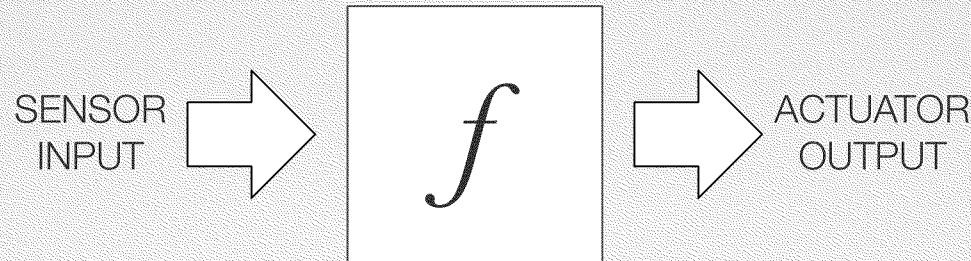


ECU Hardware

- ❖ CPU: Tricore TC1797
 - RISC processor
 - Marketed to auto industry
- ❖ Flash and EEPROM
- ❖ ADCs, line drivers, etc.



ECU Software



- ❖ ERCOS operating system (marketed to auto industry)
- ❖ Continuous control loop evaluation
 - Read sensor input
 - Evaluate control function
 - Write actuator output

Car Maker ≠ ECU Maker

- ❖ ECU made by third party, not automaker
- ❖ All ECUs implicated in emissions cheating made by Robert Bosch GmbH  **BOSCH**
 - EDC17: “Electronic Diesel Control”
- ❖ Bosch makes the hardware and writes software
- ❖ ECU code customized for each customer (automaker)

Calibration

EGR rate		RPM															
mm ³		600	650	900	1,000	1,250	1,500	1,600	1,750	2,000	2,150	2,250	2,500	2,750	3,250	3,500	3,750
2.5	0.0	46.0	46.0	43.0	40.0	30.0	25.0	22.0	15.0	5.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
5.0	0.0	48.0	48.0	47.0	47.0	47.0	47.0	45.0	42.0	5.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
10.0	0.0	48.0	48.0	47.0	47.0	47.0	47.0	45.0	42.0	5.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
12.5	0.0	46.0	46.0	46.0	46.0	47.0	47.0	45.0	42.0	7.5	2.5	0.0	0.0	0.0	0.0	0.0	0.0
15.0	0.0	45.0	45.0	45.0	45.0	45.0	45.0	45.0	40.0	10.0	5.0	0.0	0.0	0.0	0.0	0.0	0.0
17.5	0.0	40.0	40.0	40.0	40.0	40.0	40.0	38.0	35.0	12.5	6.3	0.0	0.0	0.0	0.0	0.0	0.0
20.0	0.0	35.0	35.0	35.0	35.0	35.0	35.0	35.0	30.0	15.0	7.5	0.0	0.0	0.0	0.0	0.0	0.0
22.5	0.0	26.0	26.0	28.5	29.0	30.0	30.0	30.0	30.0	17.5	8.8	0.0	0.0	0.0	0.0	0.0	0.0
25.0	0.0	20.0	20.0	25.0	25.0	27.5	27.5	27.5	27.5	20.0	10.0	0.0	0.0	0.0	0.0	0.0	0.0
27.5	0.0	15.5	15.5	20.0	22.5	25.0	25.0	25.0	25.0	22.5	11.3	0.0	0.0	0.0	0.0	0.0	0.0
30.0	0.0	10.0	10.0	16.0	17.0	20.0	20.0	20.0	20.0	20.0	12.5	0.0	0.0	0.0	0.0	0.0	0.0
35.0	0.0	5.0	5.0	8.0	12.0	17.0	18.0	18.0	18.0	18.0	10.5	0.0	0.0	0.0	0.0	0.0	0.0
40.0	0.0	0.0	0.0	0.0	6.5	13.0	15.0	15.0	15.0	15.0	5.0	0.0	0.0	0.0	0.0	0.0	0.0
50.0	0.0	0.0	0.0	0.0	0.0	5.0	10.0	10.0	10.0	5.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
55.0	0.0	0.0	0.0	0.0	0.0	0.0	5.0	5.0	5.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
60.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

❖ Calibration performed by automaker

- Some constants may be calibrated by ECU maker

Software Documentation

- ❖ Carmaker relies on software documentation provided by ECU maker to calibrate firmware
- ❖ ECU documentation are called function sheets (*funktionsrahmen*)
- ❖ Functions described using dataflow diagrams
- ❖ Some function sheets leaked to car tuner community



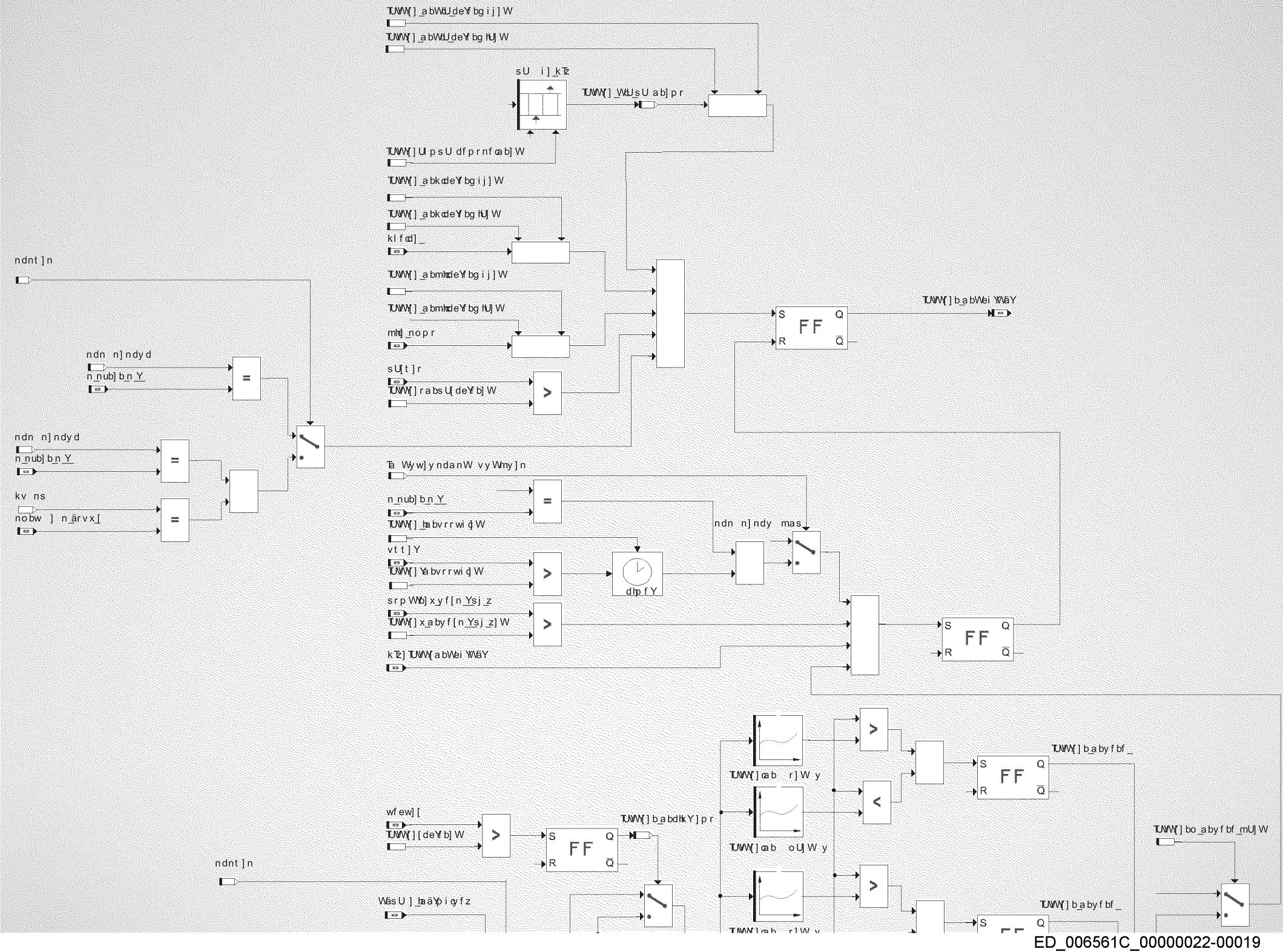
Volkswagen Defeat Device

- ❖ 74. Audi developed and deployed this cycle-beating defeat device software on its European-market Audi 3.0 liter V6 diesels from 2004-2008. Because of its noise-reducing properties, Audi dubbed this defeat device the “Acoustic Function.”
- ❖ ~~I first suspected May 15, 2014. West Virginia University road tests find 2012 Jetta emits 15-35 times the allowed NOx~~
- ❖ Existence public **September 18, 2015:** EPA Notice of Violation to VW

Acoustic Function

- ❖ Variable indicating if vehicle is under test
 - **InjCrv_stNsCharCor = 0:** normal driving
 - **InjCrv_stNsCharCor = 1:** emissions test
- ❖ Computed by InjCrv_CoPiIRlsOpRng function
- ❖ Used in multiple systems to alter vehicle behavior
 - EGR, DPF, SCR, Fuel injection

Abbildung 1997 Freigabestruktur der Akustikbedingung [injcrv_copiirlsoprng_3]



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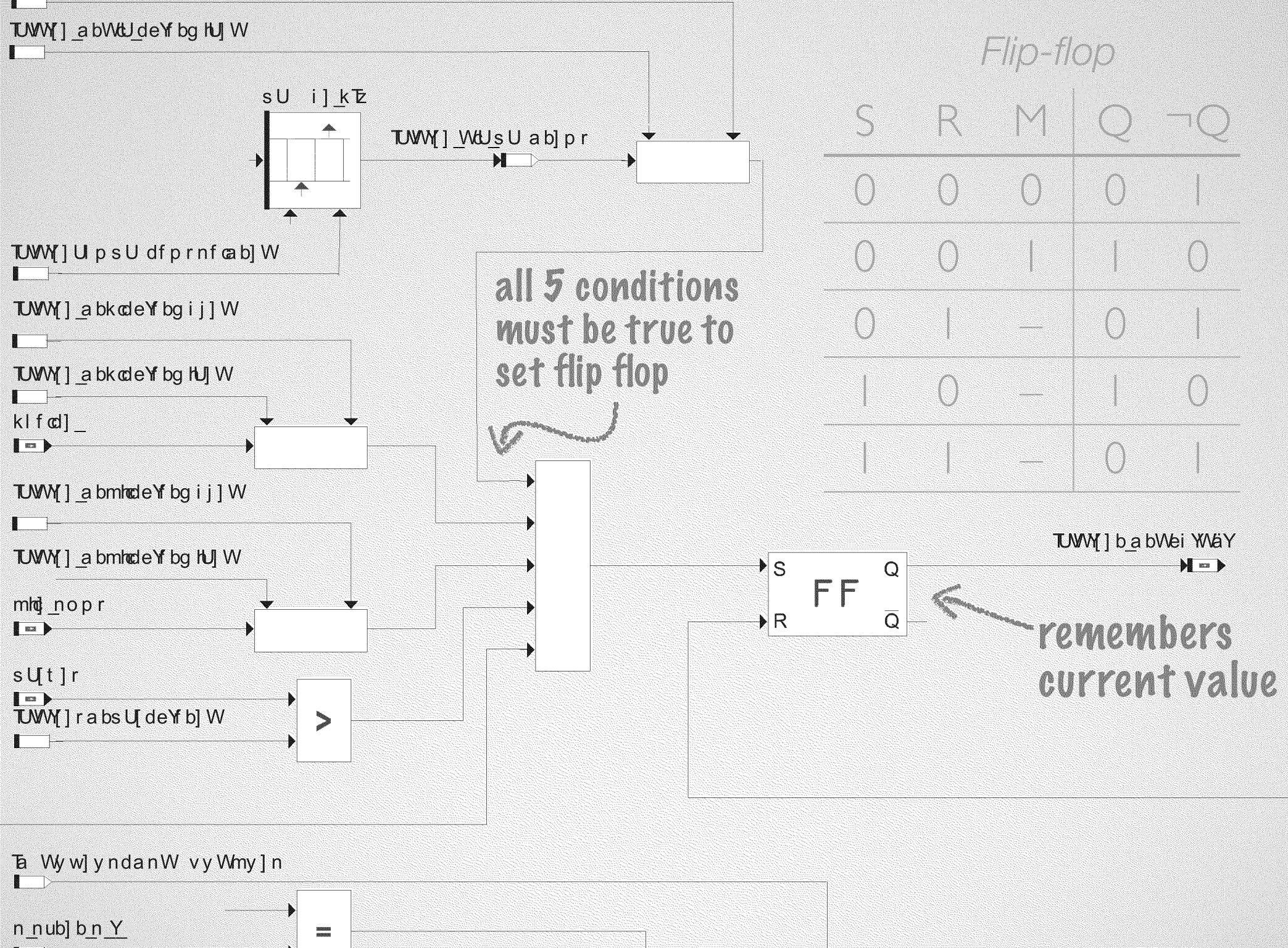
Flip-flop

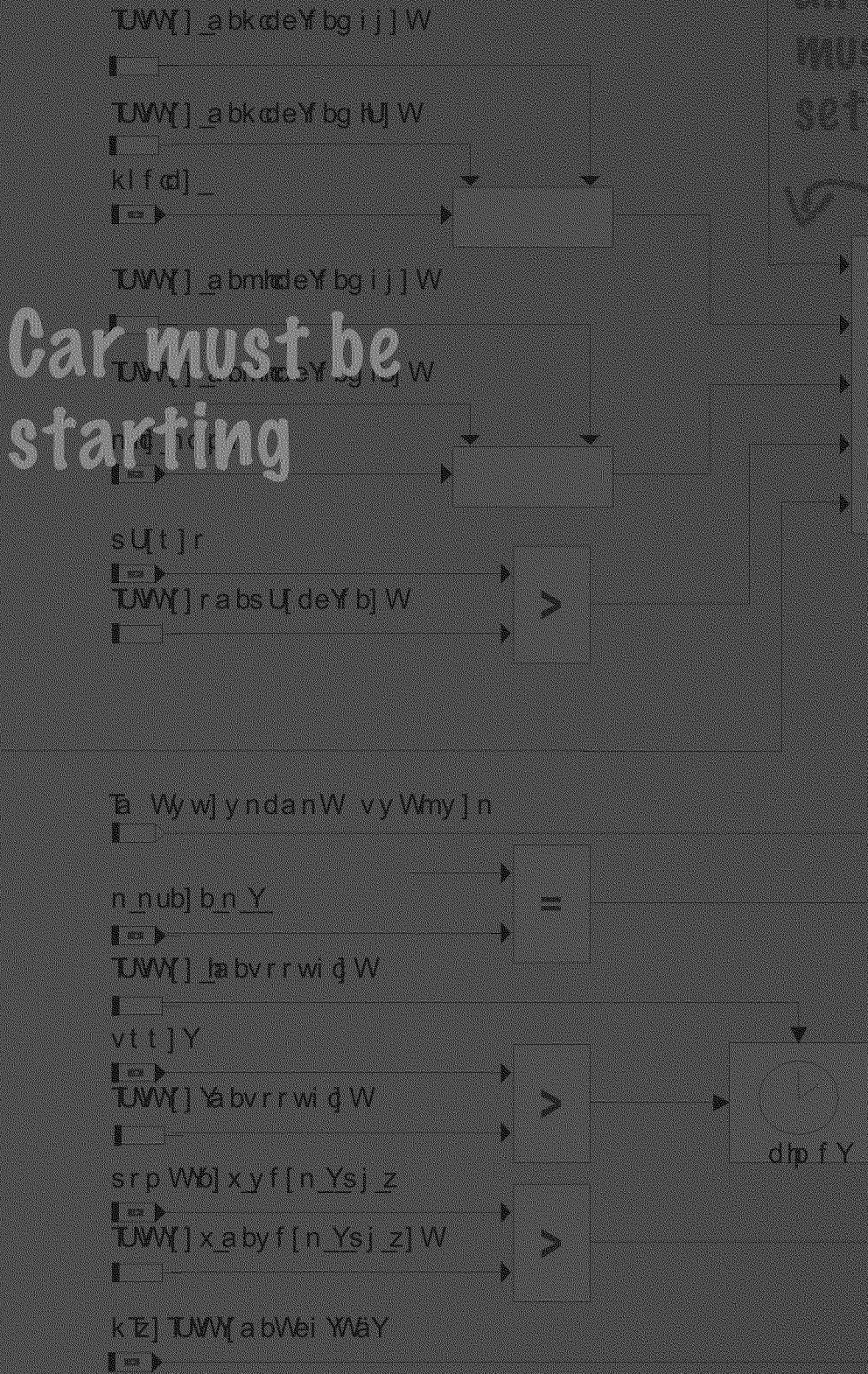
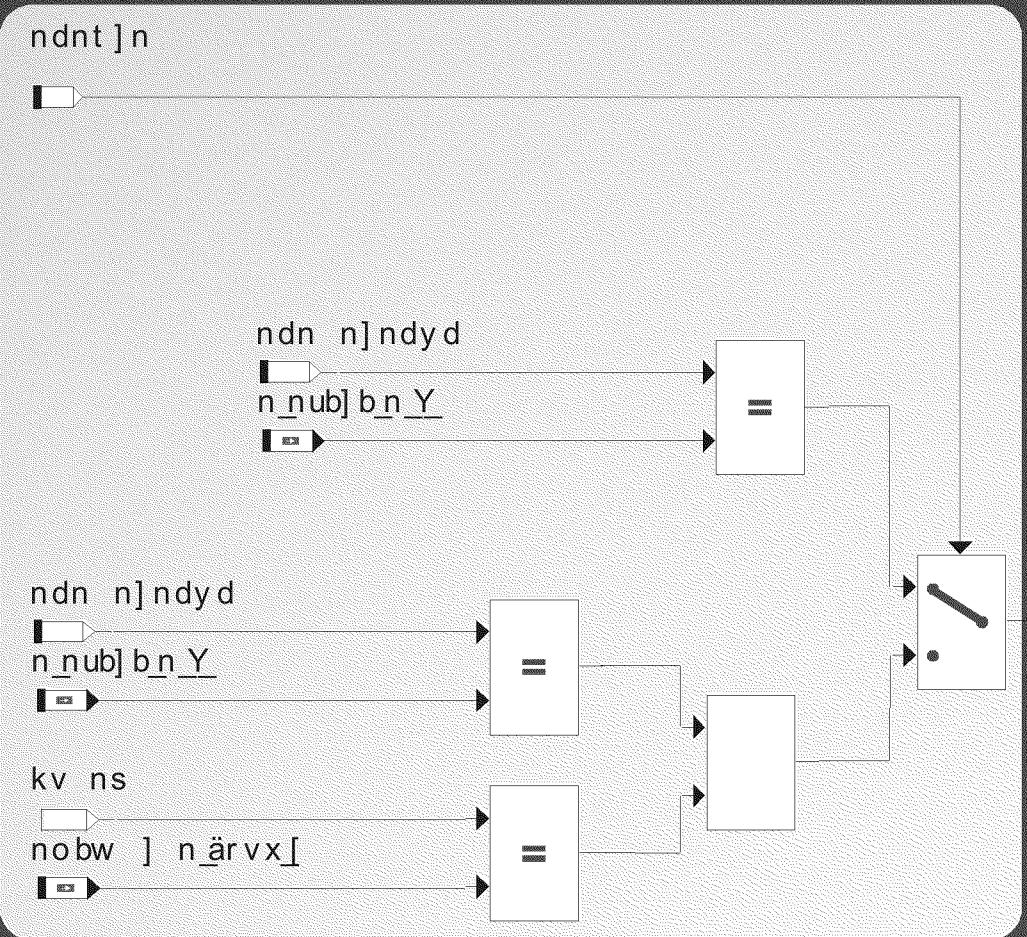
S	R	M	Q	\bar{Q}
0	0	0	0	1
0	0	1	1	0
0	1	-	0	1
1	0	-	1	0
1	1	-	0	1

all 5 conditions
must be true to
set flip flop

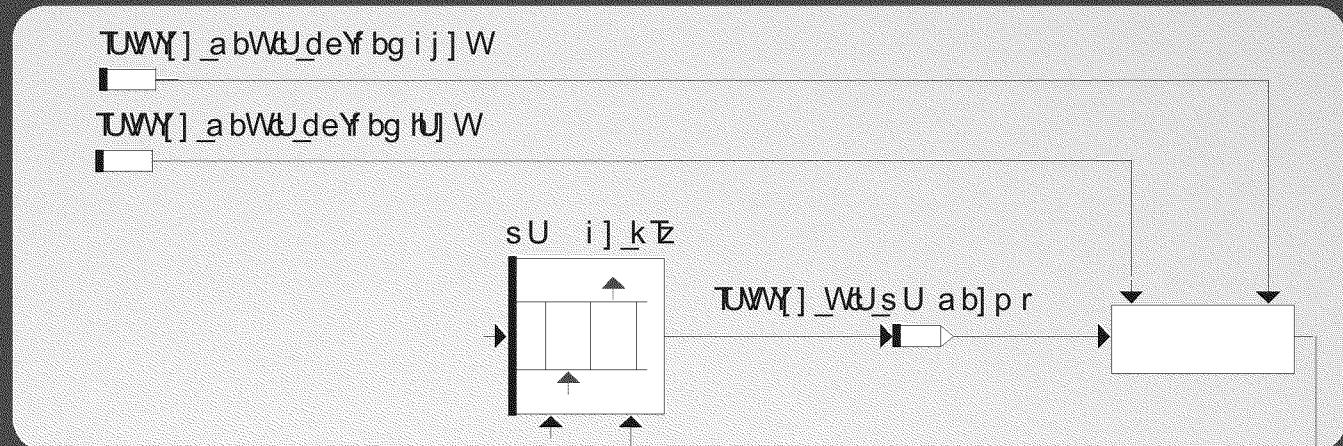
TWW[] b_a bWe i W&Y

remembers
current value

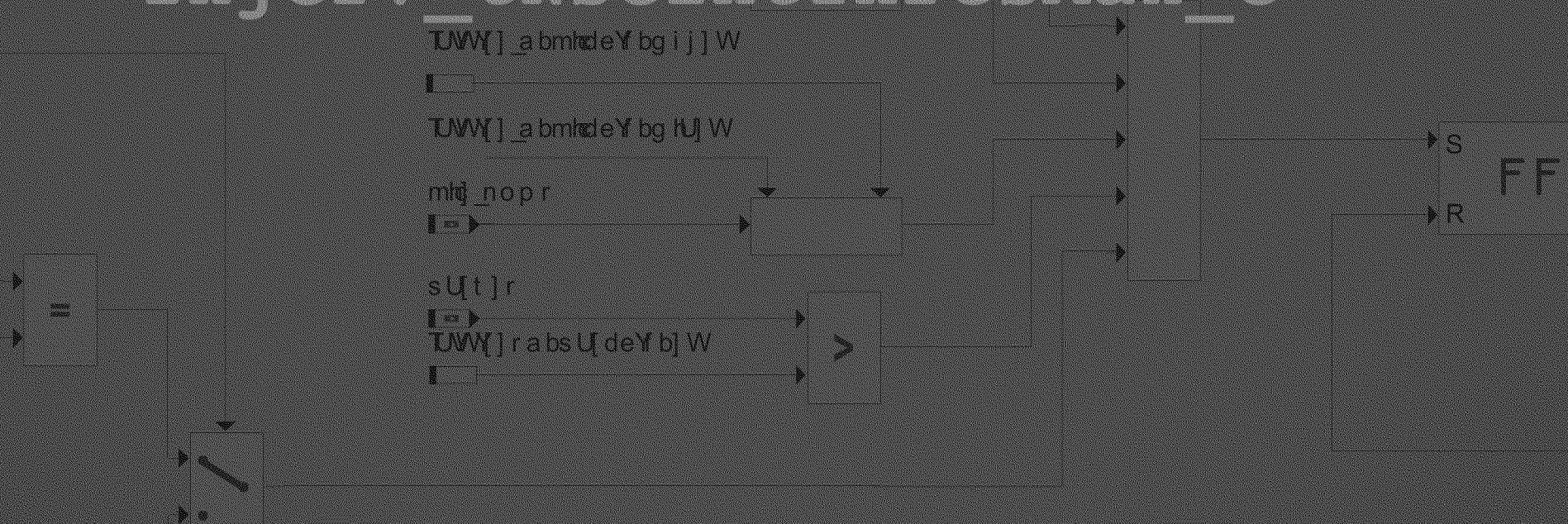




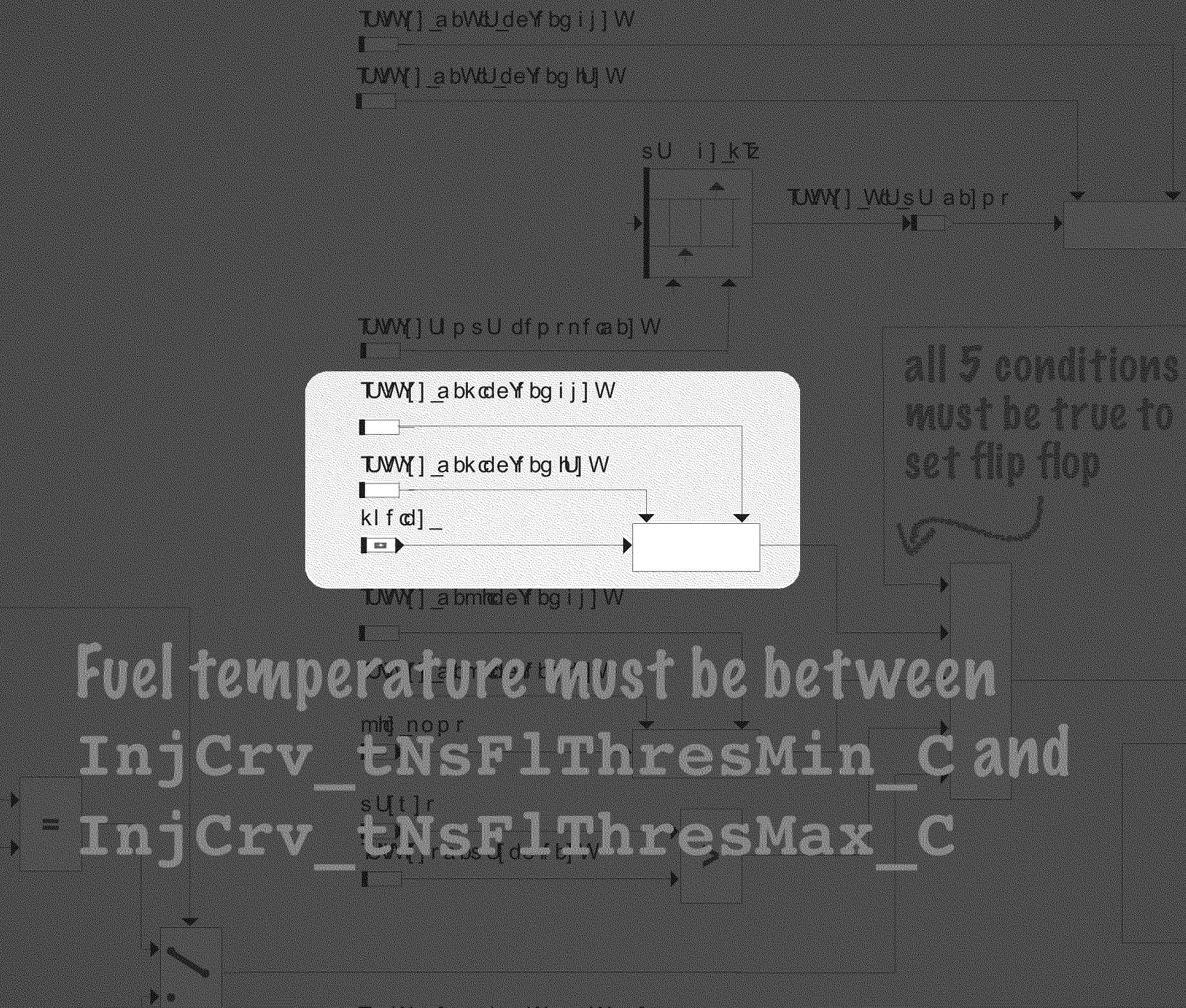
Freigabestruktur der Akustikbedingung [injcrv_copiirlsoprng_3]



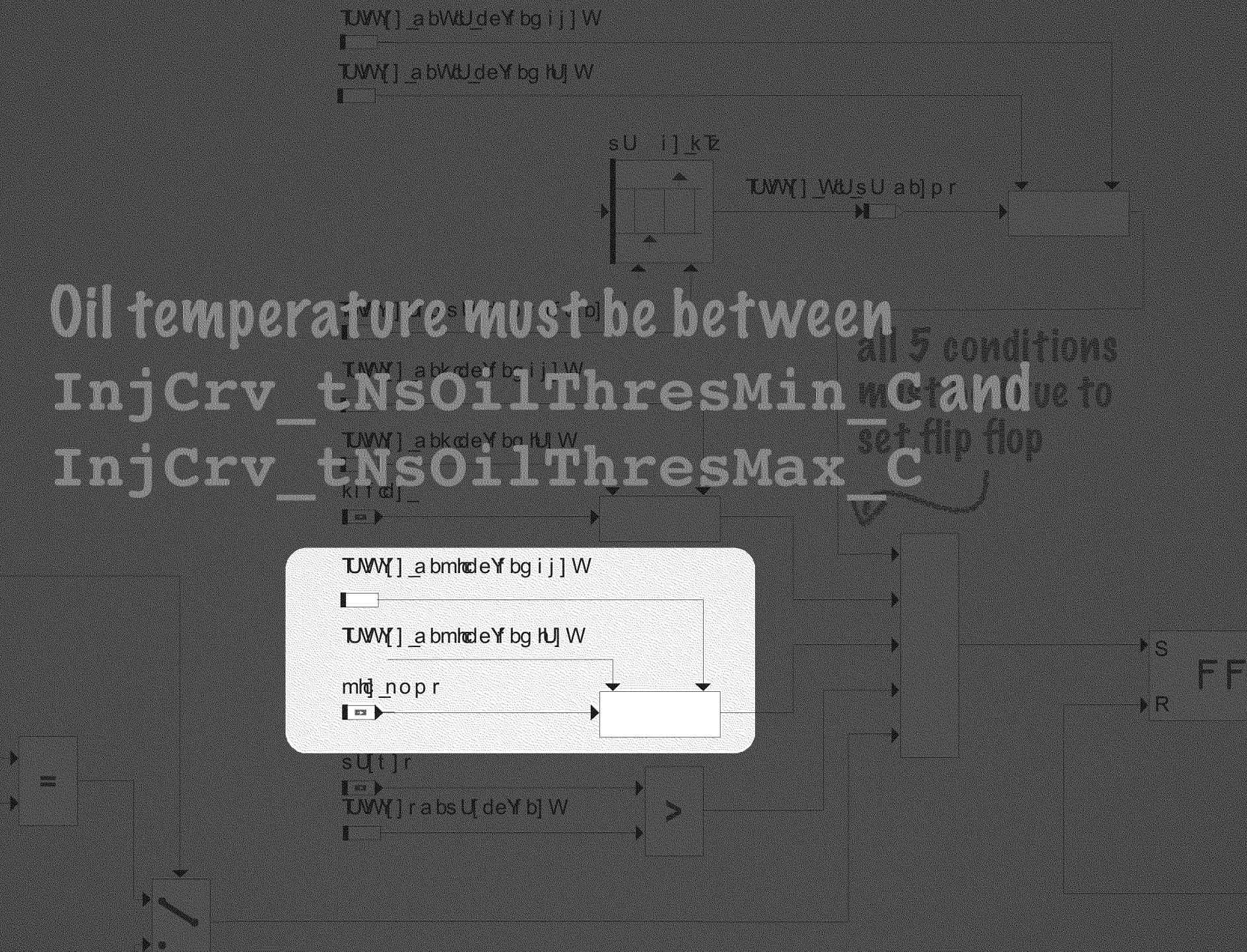
Coolant temperature must be between
InjCrv_tNsCln~~t~~ThresMin_C and
InjCrv_tNsCln~~t~~ThresMax_C



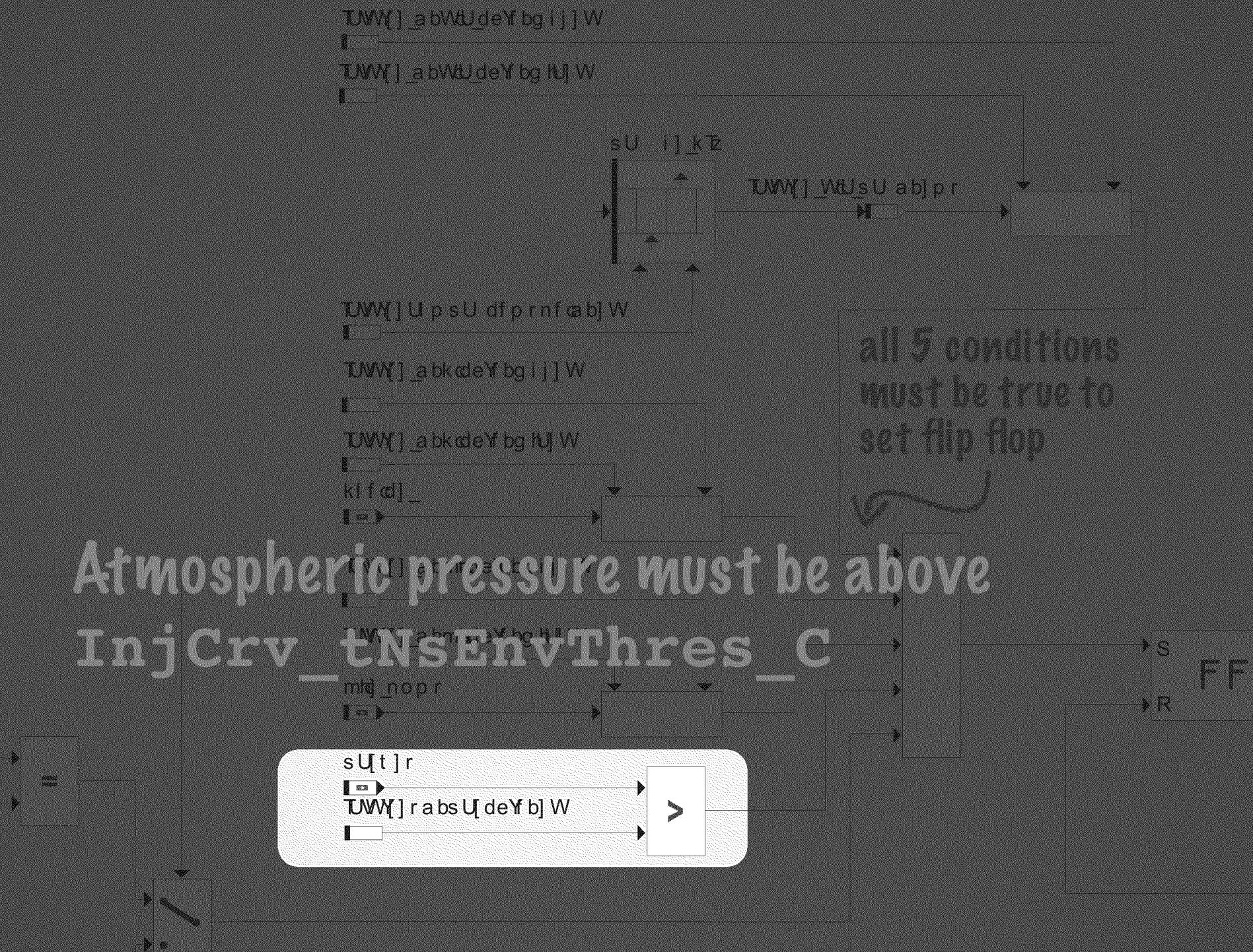
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Freigabestruktur der Akustikbedingung [injcrv_copiirlsoprng_3]



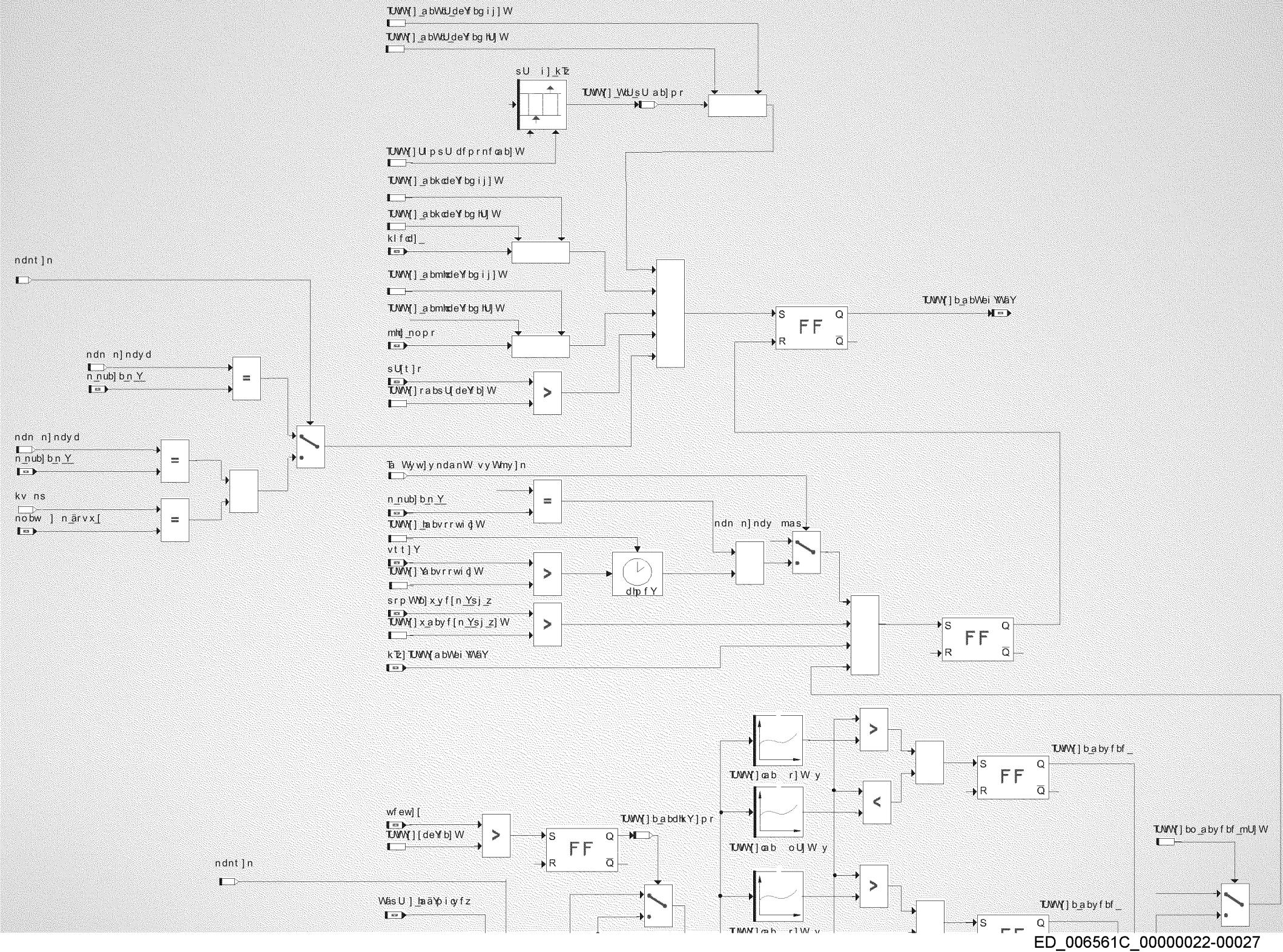
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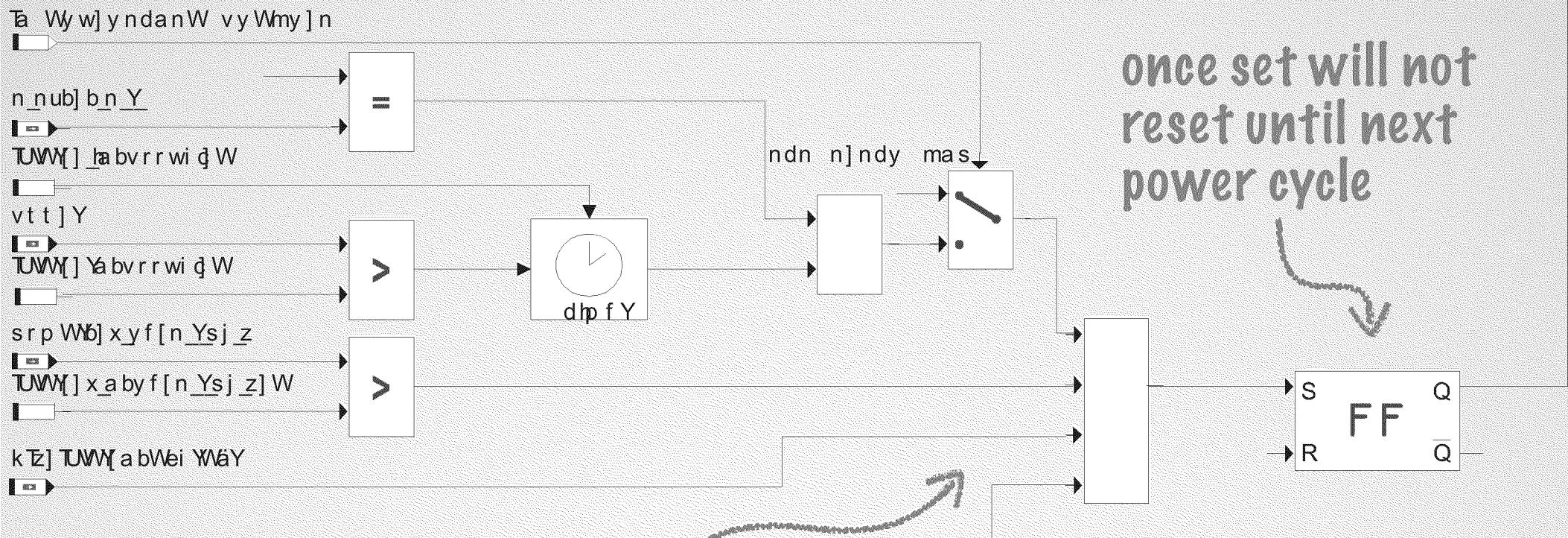
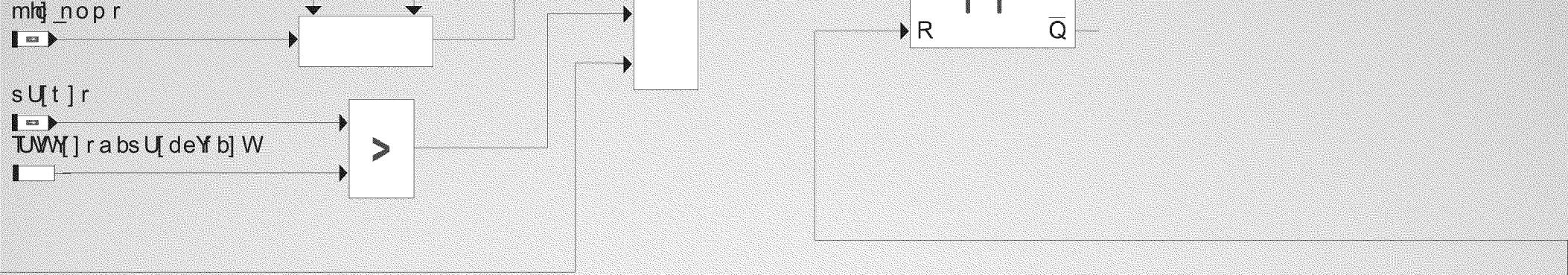
Acoustic Condition: Activation

- ❖ Acoustic condition will activate (assume car under test) if all environmental conditions are within specific limits
 - Coolant temperature
 - Fuel temperature
 - Oil temperature
 - Atmospheric pressure (proxy for altitude)

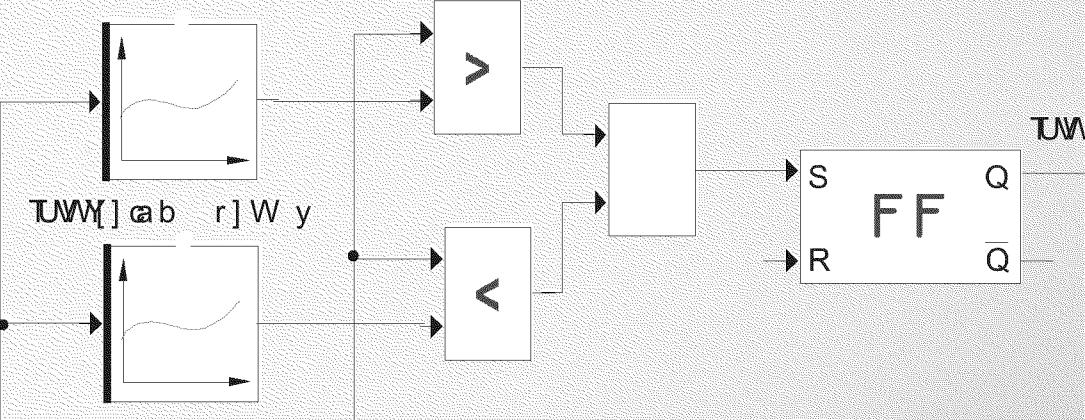
Abbildung 1997 Freigabestruktur der Akustikbedingung [injcrv_copiirlsoprng_3]



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any of the 4 conditions will set flip flop and deactivate acoustic condition



Ta Wy w] y nda nW vy Wmy] n

n_n ub] b_n Y

TWW] _habvrrwi q W

vt t] Y

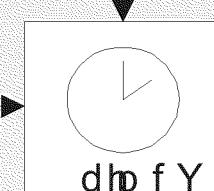
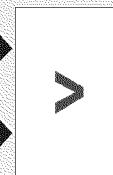
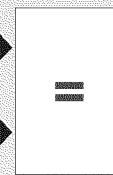
TWW] Yabvrrwi q W

srp Wb] x_yf [n_Ysj_z

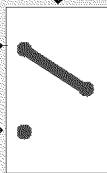
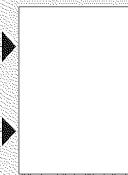
TWW] xabyf [n_Ysj_z] W

k Tz] TWW] abWei yway

TWW]



ndn n] ndy mas



Accelerator pedal at InjCrv_rNsAppVal_C
for more than InjCrv_tNsAppVal_C
seconds and engine is not starting

TWW] ab r] W y

wf ew] [

Ta Wy w] yndanW vy Wmy] n

n_nub] b_n_Y

TWW[]_abvrrwi d W

vt t] Y

TWW[]_abvrrwi d W

srp Wb] x_yf [n_Ysj_z

TWW[] x_ab yf [n_Ysj_z] W

k Tz] TWW[a bWei YMwY

=>

Number of crankshaft revolutions exceeds

InjCrv_ctnsRevStartExtd_C

wf ew] [

TWW[ab r] W y

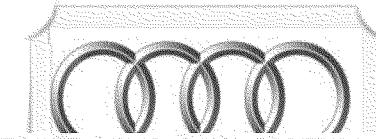
oxyvinmskrstkvmls



oxyvinmskrstkvmls



skrstlmrxn



concept of the dual-mode, emissions cycle-beating software from Audi. On or

about May 17, 2006, a VW engineer, in describing the Audi software, sent an

email to employees in the VW Brand Engine Development department that

❖ described aspects of the software and cautioned against using it in its current form

because it was “pure” cycle-beating, i.e., as a mechanism to detect, evade and

defeat U.S. emissions cycles or tests. The VW AG engineer wrote (in German),

“within the clearance structure of the pre-fuel injection the acoustic function is

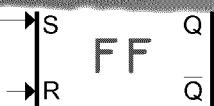
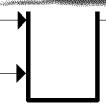
nearly always activated within our current US’07-data set. This function is pure

❖ [cycle-beating] and can like this absolutely not be used for US’07.”

oxyvinm rnis

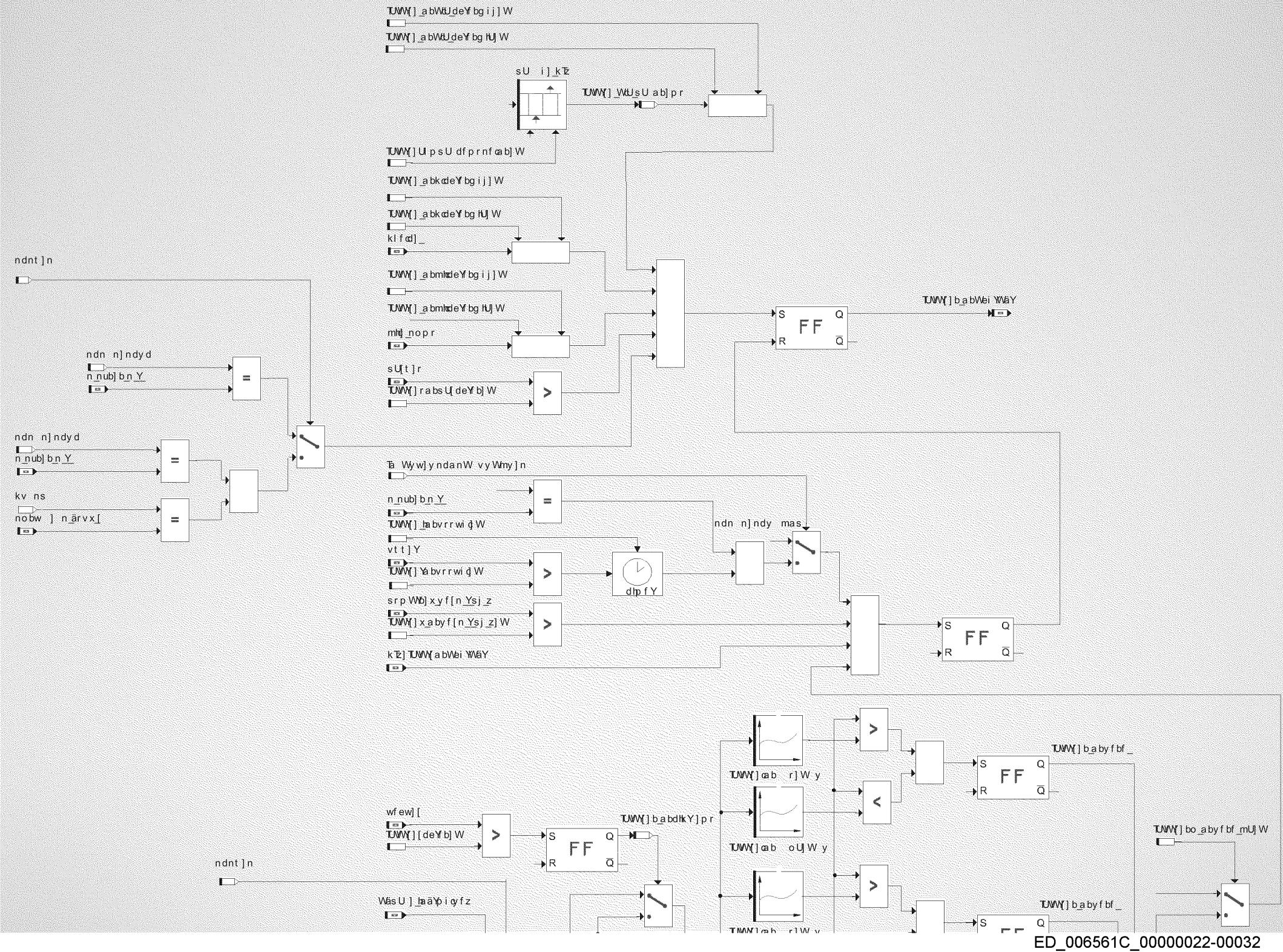


ul oxyv ms vs v

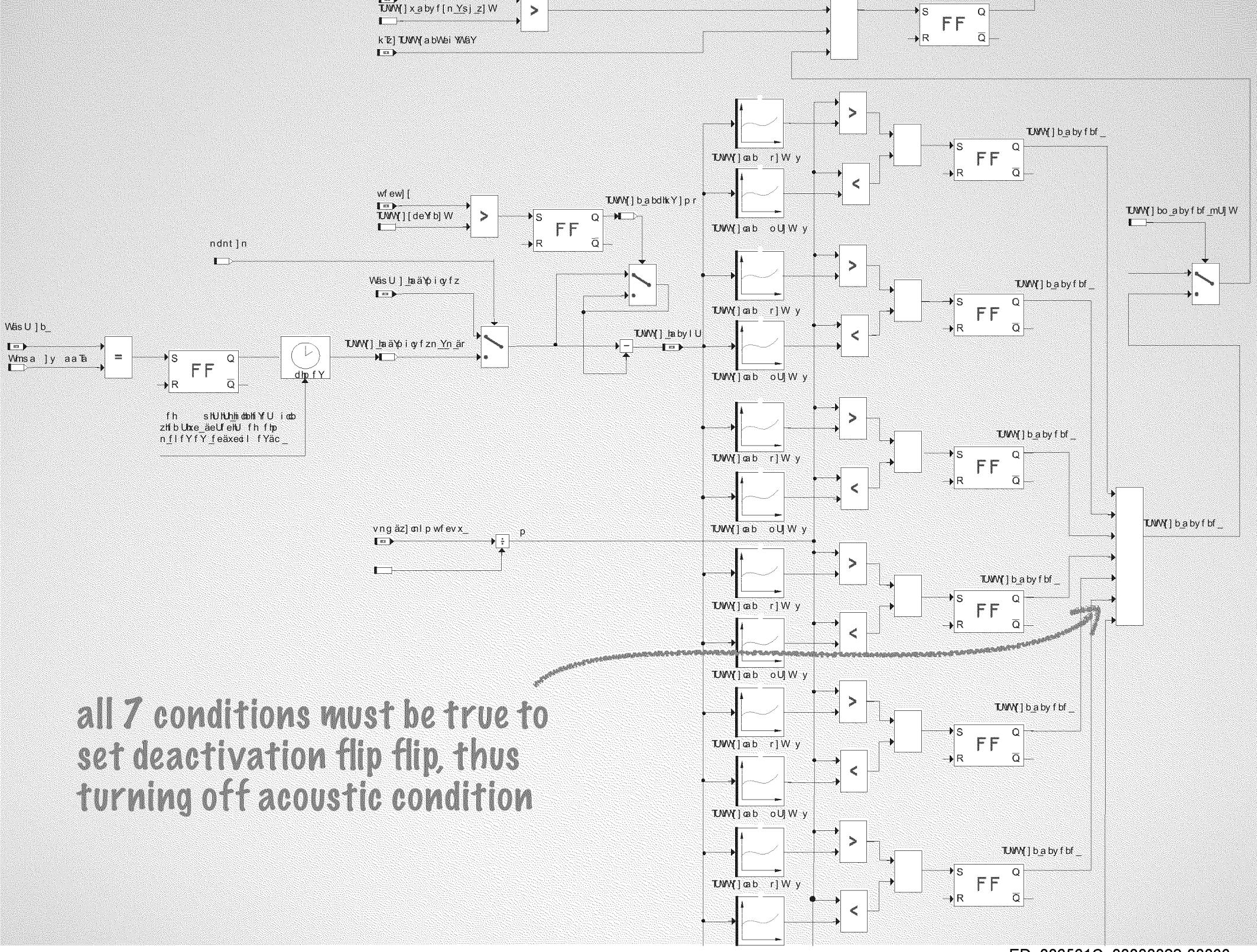


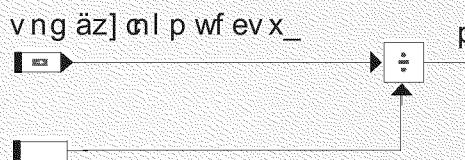
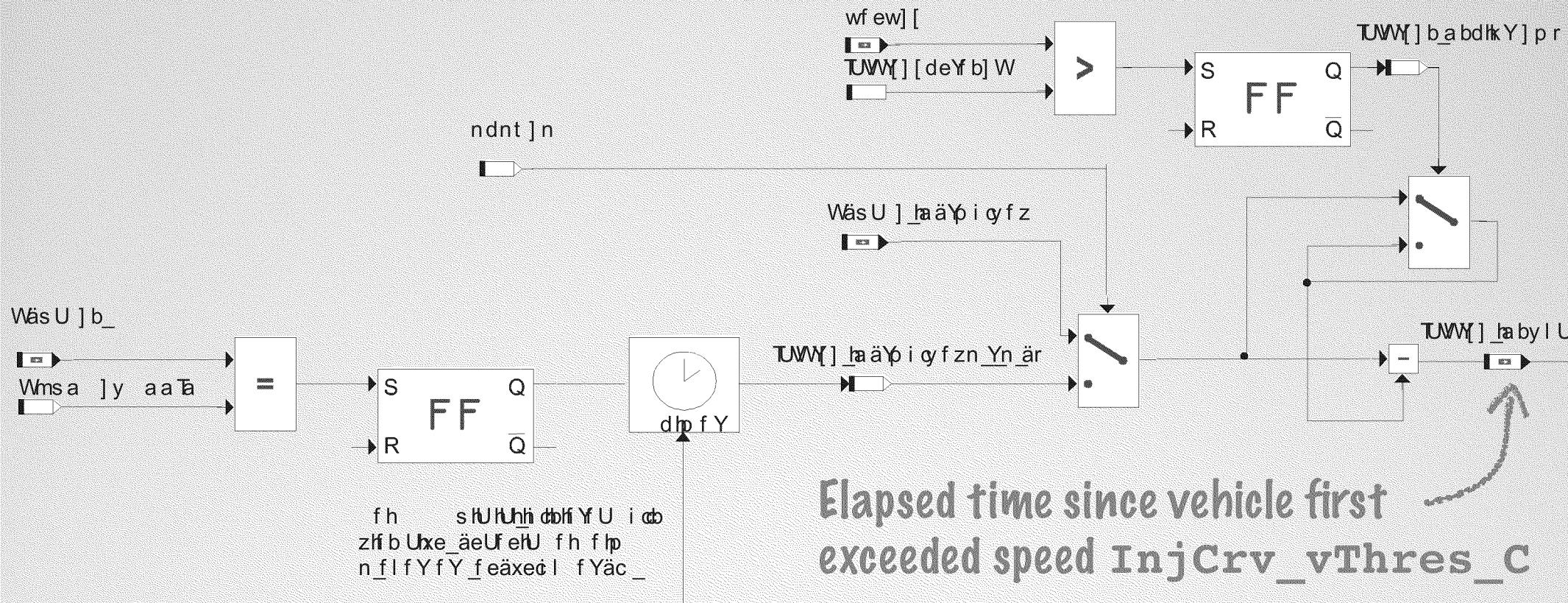
oxyv l m

Abbildung 1997 Freigabestruktur der Akustikbedingung [injcrv_copiirlsoprng_3]

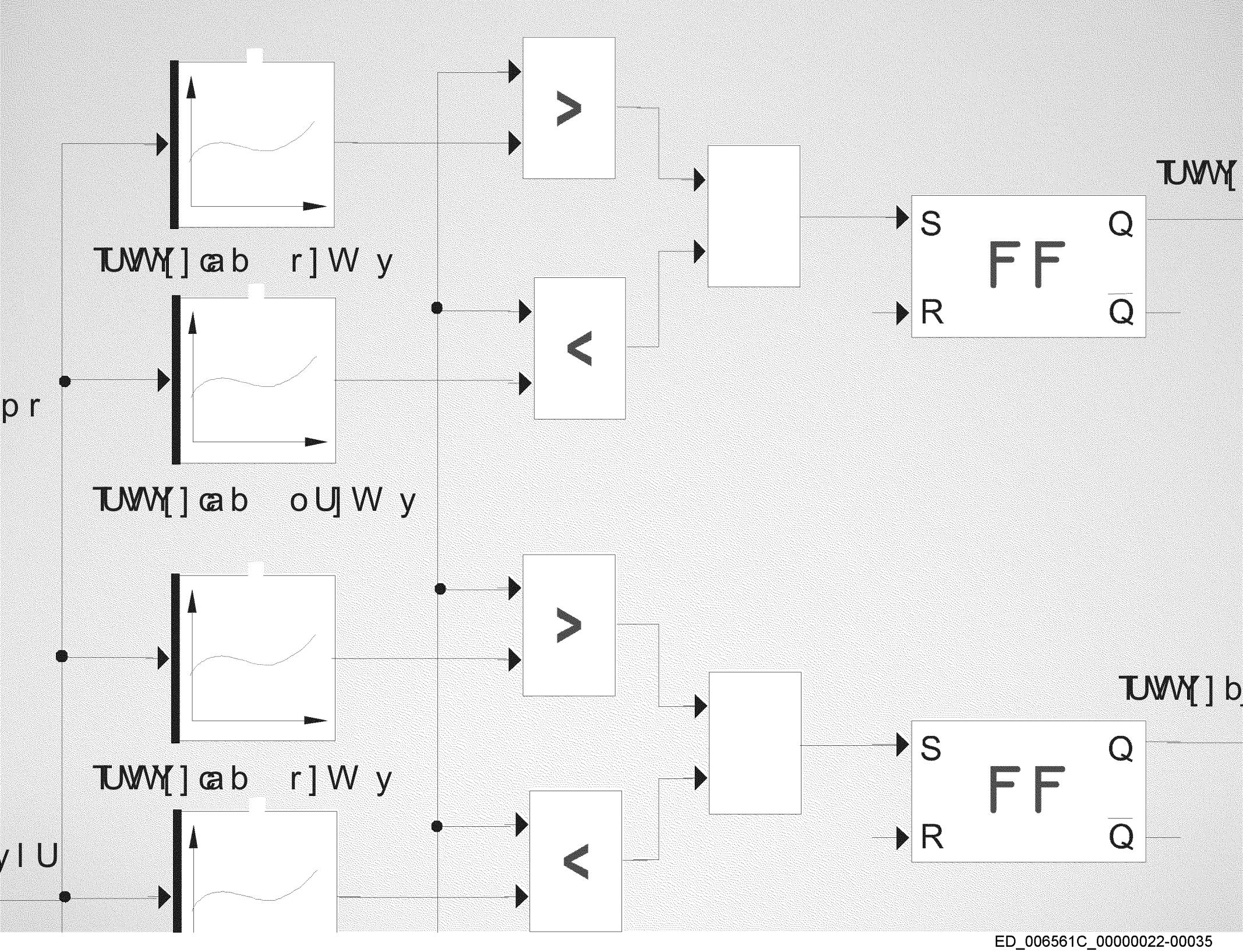


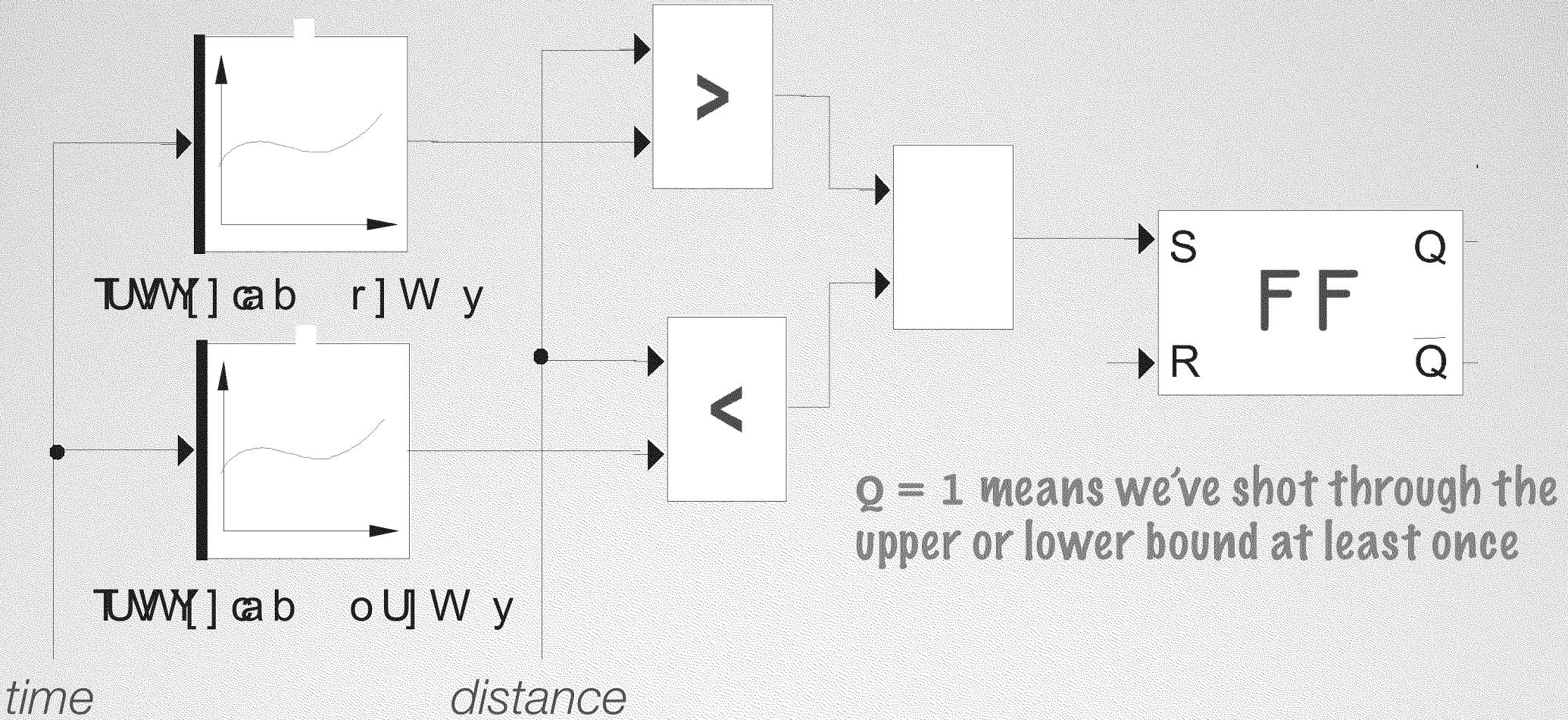
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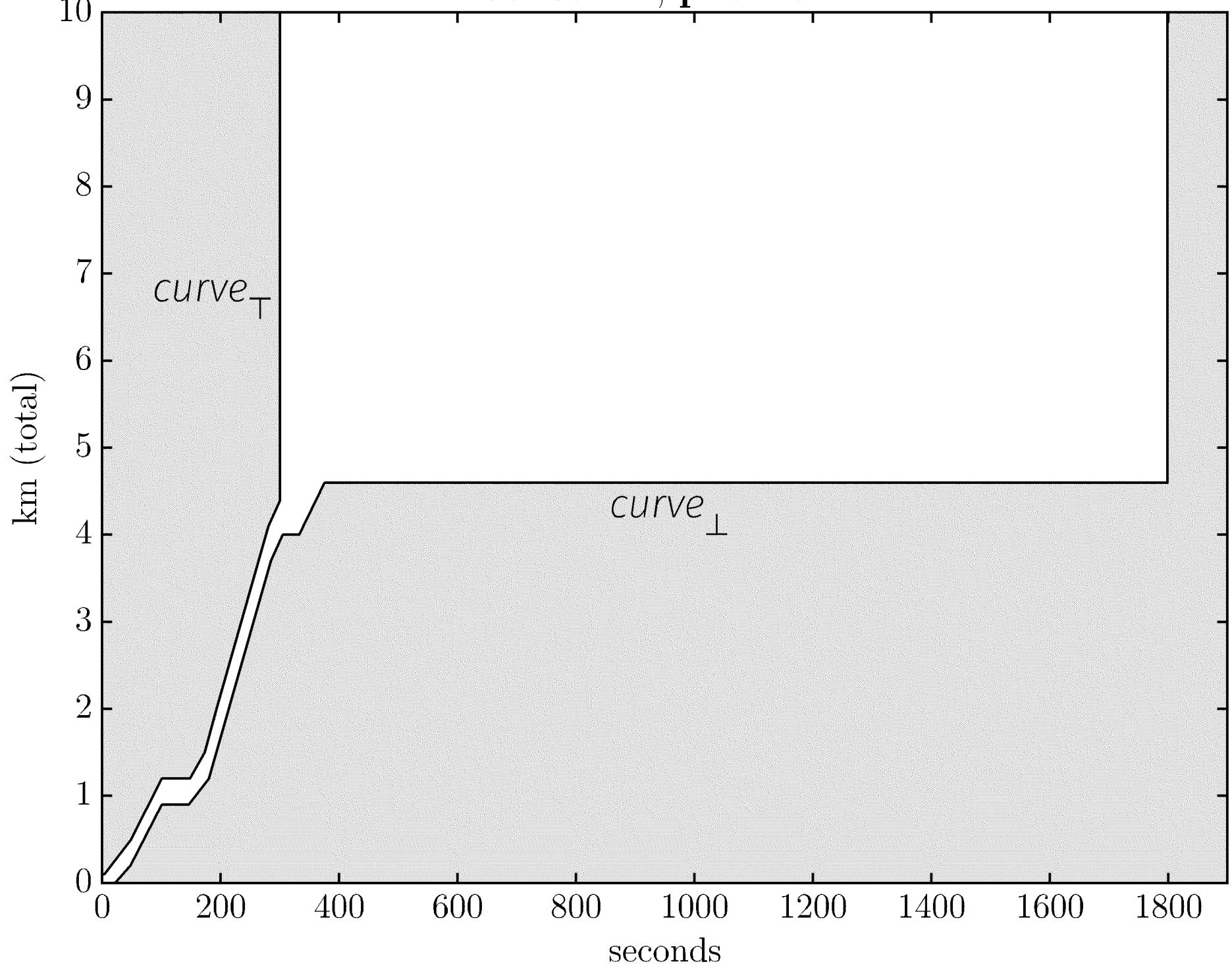
Distance traveled this driving cycle (km)



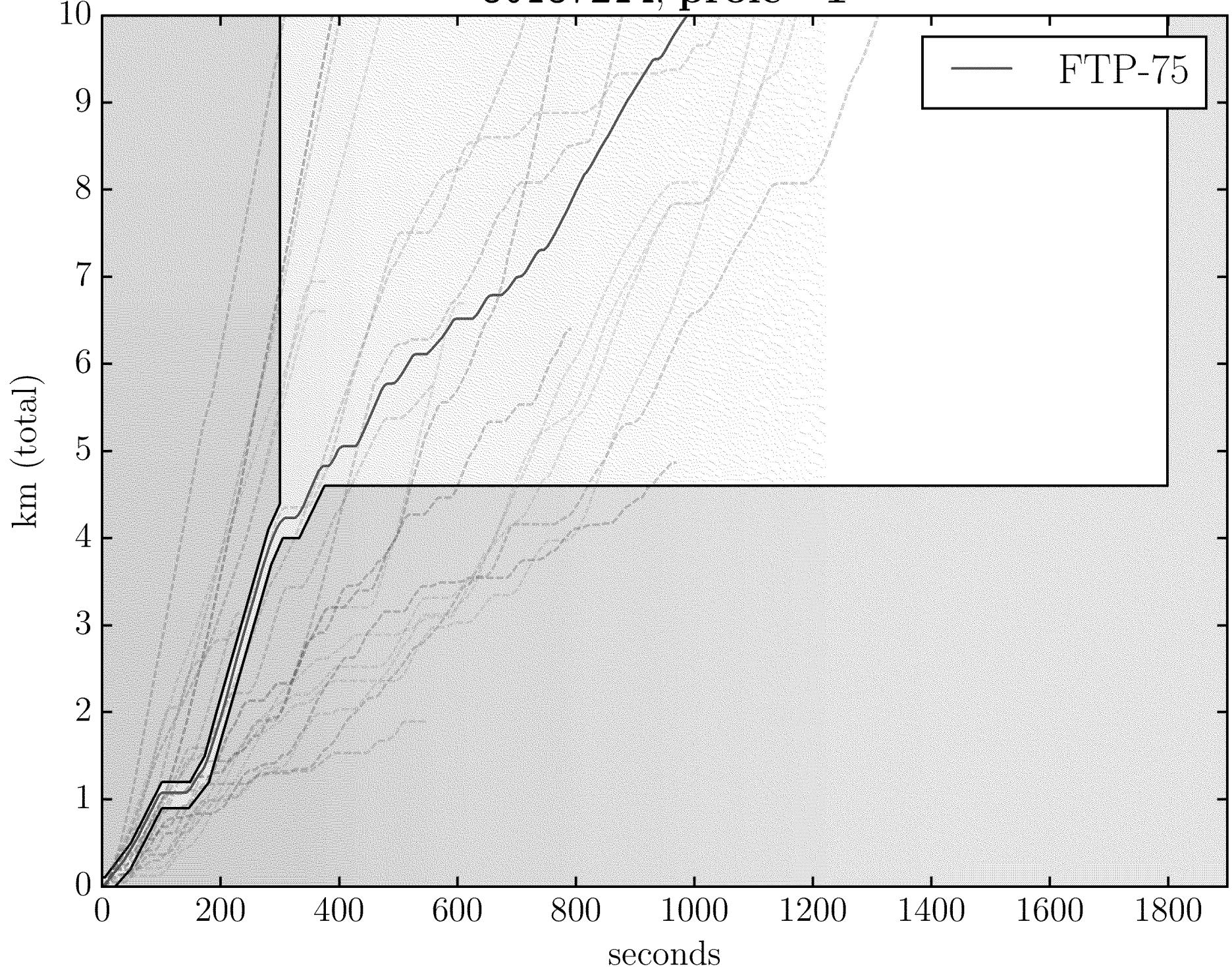


- ❖ Flip-flop will be set if distance traveled goes above upper or below lower bound
- ❖ Lower and upper bounds are a function of time
- ❖ ECU remembers this by setting flip-flop

80187214, profile 1

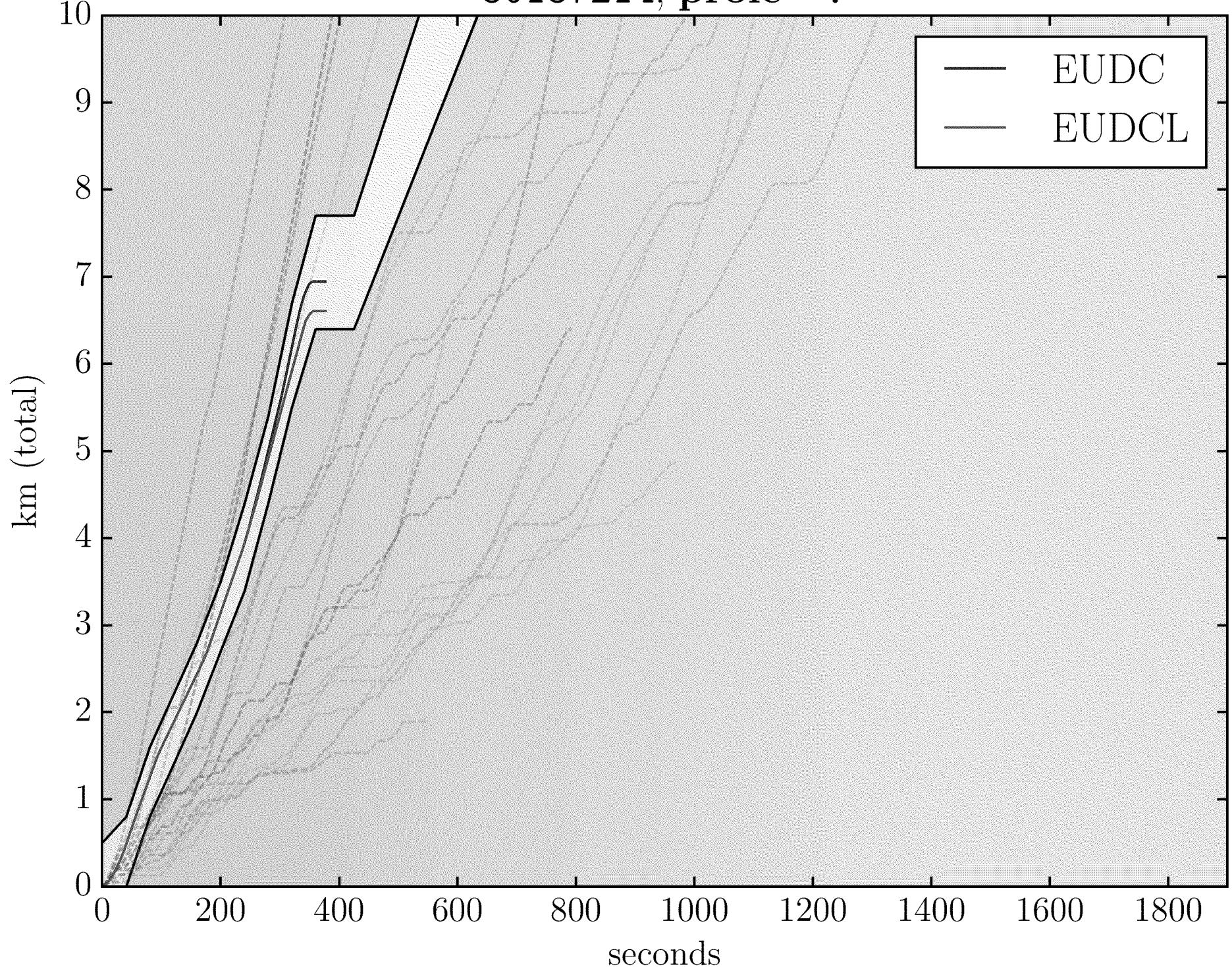


80187214, prole 1



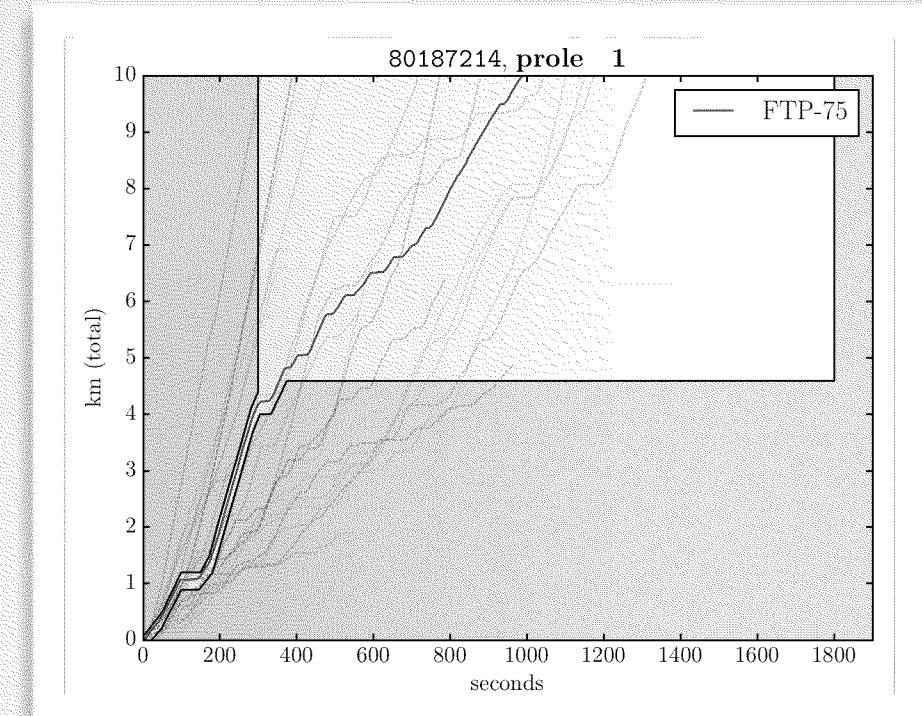
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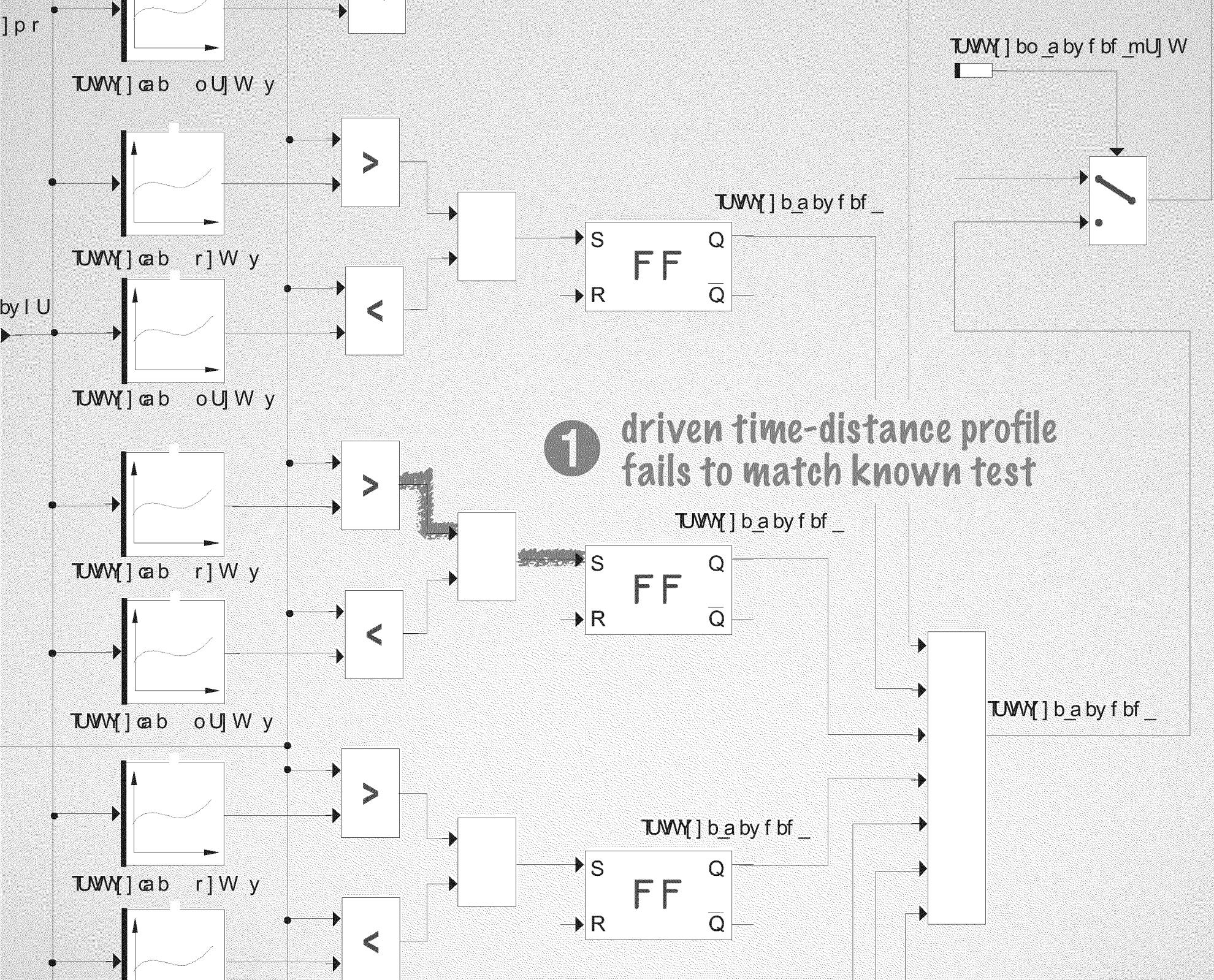
80187214, prole 7

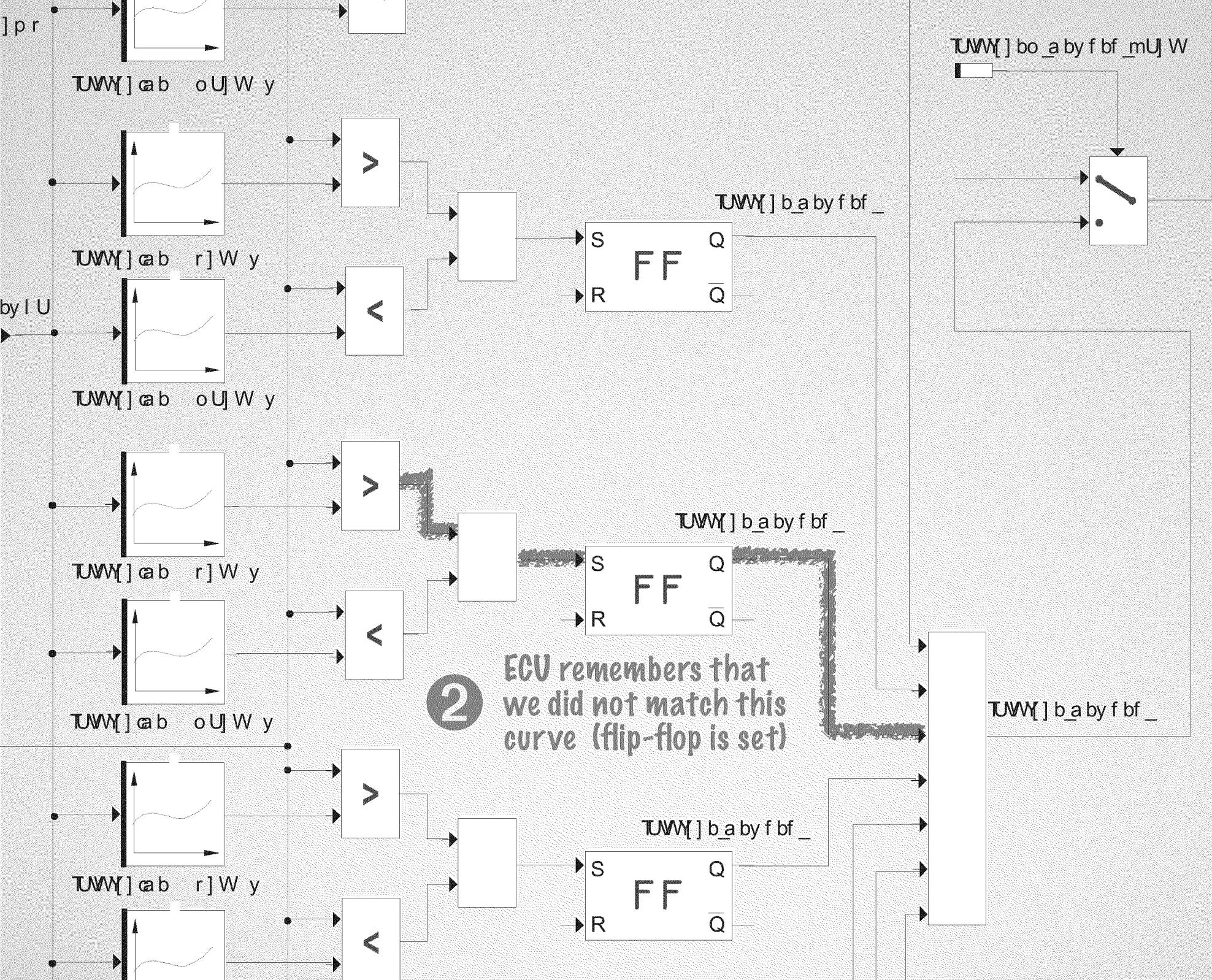


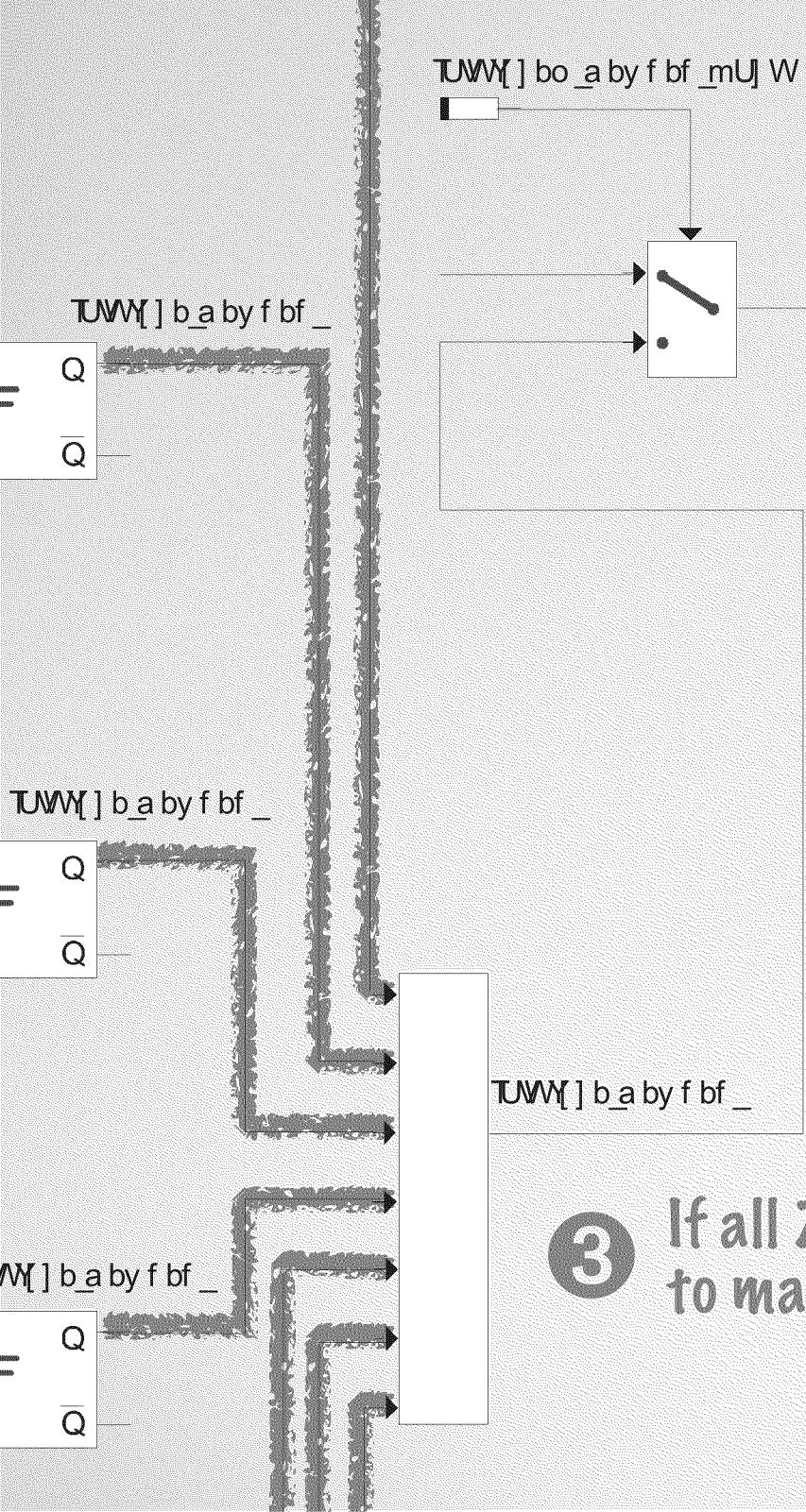
Time-Distance Curves

- ❖ Exceeding upper or lower bound will set flip-flop
 - ECU remembers that curve did not match driving profile
- ❖ Once all 7 curves are ruled out acoustic condition is off









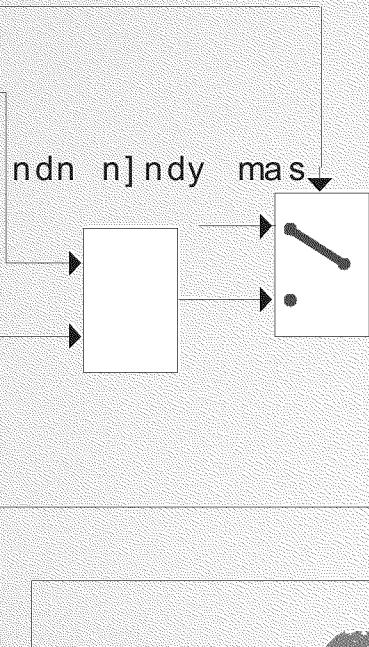
③ If all 7 curves fail
to match ...

TUN] b_a bWeiß



⑥

... and turns off acoustic condition
for rest of driving cycle



④

Deactivation
condition is met

⑤

ECU remembers this for
rest of driving cycle ...

Acoustic Condition Summary

- ❖ Environmental condition during car start determine initial state of acoustic condition
 - If temperatures and atmospheric pressure normal, assume test and activate condition (`InjCrv_stNsCharCor = 1`)
- ❖ Accelerating too much deactivates acoustic condition
- ❖ Deactivates after certain number of crankshaft revs
- ❖ Deactivates if profiles doesn't match known tests
- ❖ Later curves (ca. 2014) included a steering wheel check
 - Match fails if steering wheel deflects by more than 20°

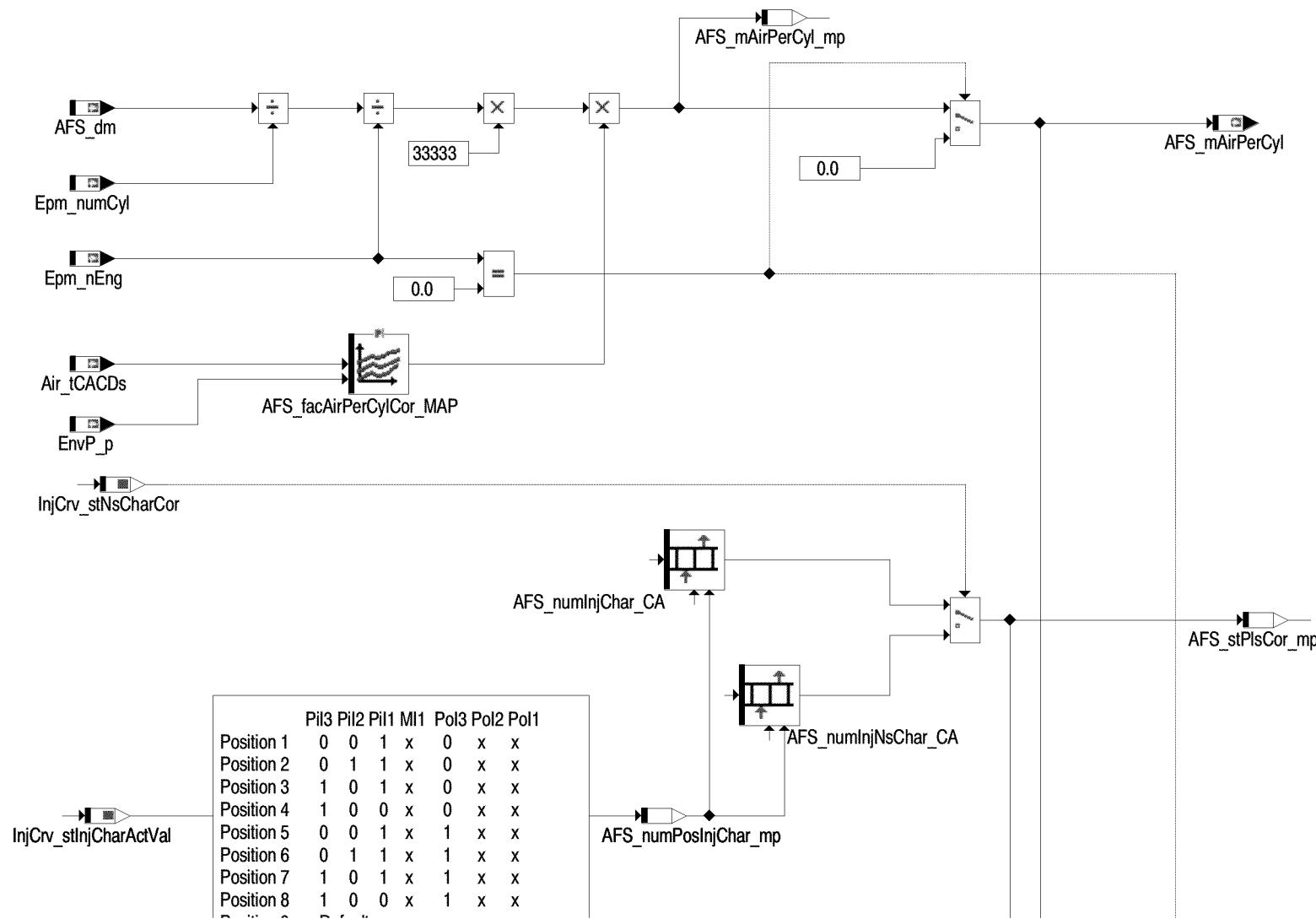
Using Acoustic Condition

- ❖ Value of acoustic condition (**InjCrv_stNsCharCor**) used to modify emissions-related system behavior
- ❖ Usually **InjCrv_stNsCharCor** switches between two parallel computations with different calibration constants
- ❖ Calibration values determine which behavior is modified and how much

(appliziert mit 0,1,2,3) eines der 3 unterschiedlichen Pulskorrekturkennfelder AFS_mPlsCor%_MAP auswählen. Zusätzlich können die Kennfelder bei aktiver Akustikfunktion (`InjCrv_stInjNsChar = 1`) über das Array `AFS_numInjNsChar_CA` getrennt appliziert werden.

Bei Drehzahl `Epm_nEng = 0` wird `AFS_mAirPerCyl` und `AFS_mAirPerCylPlsCor = 0` gesetzt

Abbildung 175 Berechnung der Luftmasse pro Zylinder [afs_7]

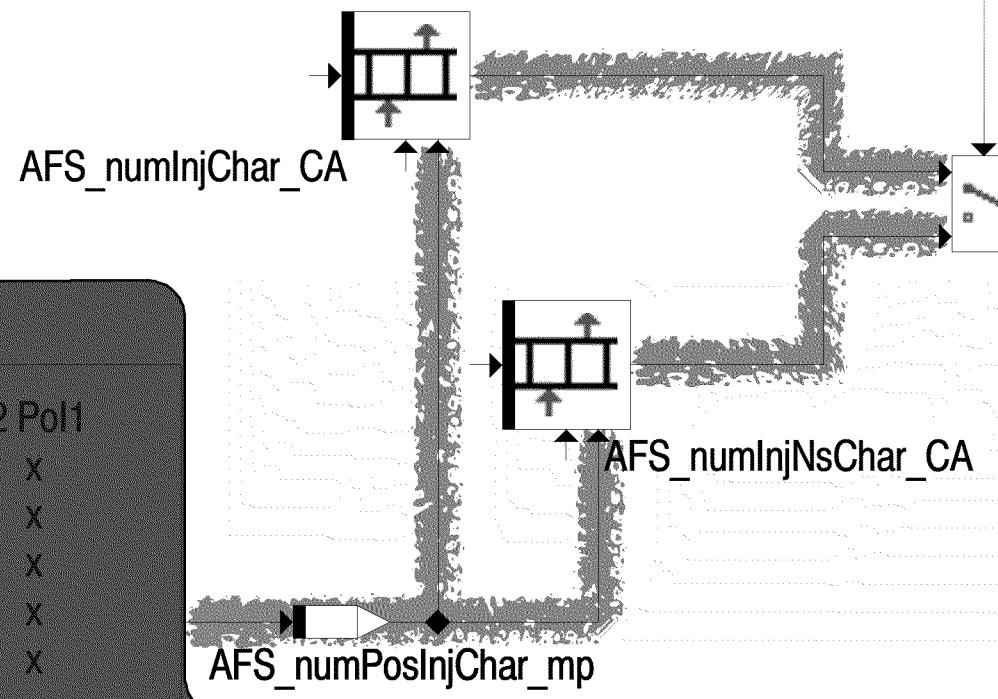




InjCrv_stNsCharCor

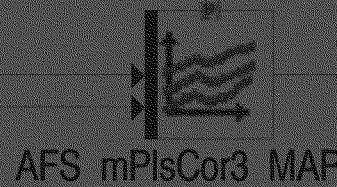
0 - real driving
1 - test cycle

	Pil3	Pil2	Pil1	MI1	Pol3	Pol2	Pol1
Position 1	0	0	1	x	0	x	x
Position 2	0	1	1	x	0	x	x
Position 3	1	0	1	x	0	x	x
Position 4	1	0	0	x	0	x	x
Position 5	0	0	1	x	1	x	x
Position 6	0	1	1	x	1	x	x
Position 7	1	0	1	x	1	x	x
Position 8	1	0	0	x	1	x	x
Position 9	Default						



Epm_nEng

AFS_SETPOINTCALC_TROBASED.SV



`AFS_numInjNsChar_CA

“noise”

- ❖ Calibration constants active during test cycle have “Ns” added to name

VW Summary

- ❖ Number of systems using **InjCrv_stNsCharCor** grew
 - Potential for modifying behavior
 - Not always enabled by VW

- ❖ Number of curves increased from 5, to 7, to 10 plus steering wheel position checks

Model	Version	Date	N	Affected Subsystems
16CP	P_397 A.V.0	2005-06-24	0	InjCrv, Rail
17CP04	P_531 2.F.0	2005-10-28	0	InjCrv
16CP	P_397 A.V.9	2006-03-02	0	InjCrv, Rail
17CP04	P_617 3.K.0	2006-11-06	0	InjCrv
17CP04	P_617 3.N.0	2006-12-22	0	InjCrv
17CP24	P_628 3.K.1	2007-03-29	—	
17CP24	P_628 3.U.0	2007-05-02	—	
17CP24	P_703 3.V.5	2007-07-12	—	
17CP04	P_617 3.U.0	2007-05-14	5	InjCrv
17CP14	P_531 3.U.0	2007-05-24	5	
17CP14	P_617 3.U.5	2007-08-30	5	
17CP24	P_628 3.W.5	2007-09-18	—	AirCtl, InjCrv
17CP14	P_714 3.U.A	2007-10-12	5	InjCrv
17CP24	P_703 3.W.A	2007-11-05	—	AirCtl, InjCrv
17CP24	P_628 3.W.G	2008-02-12	5	AirCtl, PFlt, InjCrv
17CP24	P_703 3.W.G	2008-02-14	5	AirCtl, PFlt, InjCrv
17CP24	P_628 3.W.H	2008-03-04	5	AirCtl, PFlt, InjCrv
17CP14	P_804 4.F.0	2008-03-26	5	InjCrv, Rail
17CP24	P_703 3.W.K	2008-04-23	5	AirCtl, PFlt, InjCrv
17CP24	P_628 3.W.L	2008-05-17	5	AirCtl, SCRFFC, PFlt, InjCrv
17CP24	P_859 4.F.0	2008-05-30	5	AirCtl, PFlt, InjCrv, Rail
17CP24	P_628 3.W.M	2008-06-27	5	AirCtl, SCRFFC, PFlt, InjCrv
17CP44	P_804 4.P.0	2008-08-05	—	AFS, AirCtl, ASMod, InjCrv, PCR, Rail
17CP24	P_859 4.P.0	2008-09-18	—	AFS, AirCtl, ASMod, InjCrv, PCR, PFlt, Rail
17CP44	P_930 4.P.5	2008-11-13	—	AFS, AirCtl, ASMod, InjCrv, PCR, PFlt, PFltPop, Rail
17CP44	P_804 5.A.0	2009-01-22	7	AFS, AirCtl, ASMod, InjCrv, InjSys, PCR, PFltPop, Rail, SmkLim
17CP44	P_804 5.A.5	2009-02-04	7	AFS, AirCtl, ASMod, InjCrv, InjSys, PCR, PFltPop, Rail, SmkLim
17CP44	P_859 5.A.0	2009-03-16	7	AFS, AirCtl, ASMod, InjCrv, InjSys, PCR, PFlt, PFltPop, Rail, SmkLim
17CP44	P_859 5.F.5	2009-07-13	7	AFS, AirCtl, ASMod, InjCrv, InjSys, PCR, PFlt, PFltPop, Rail, SmkLim

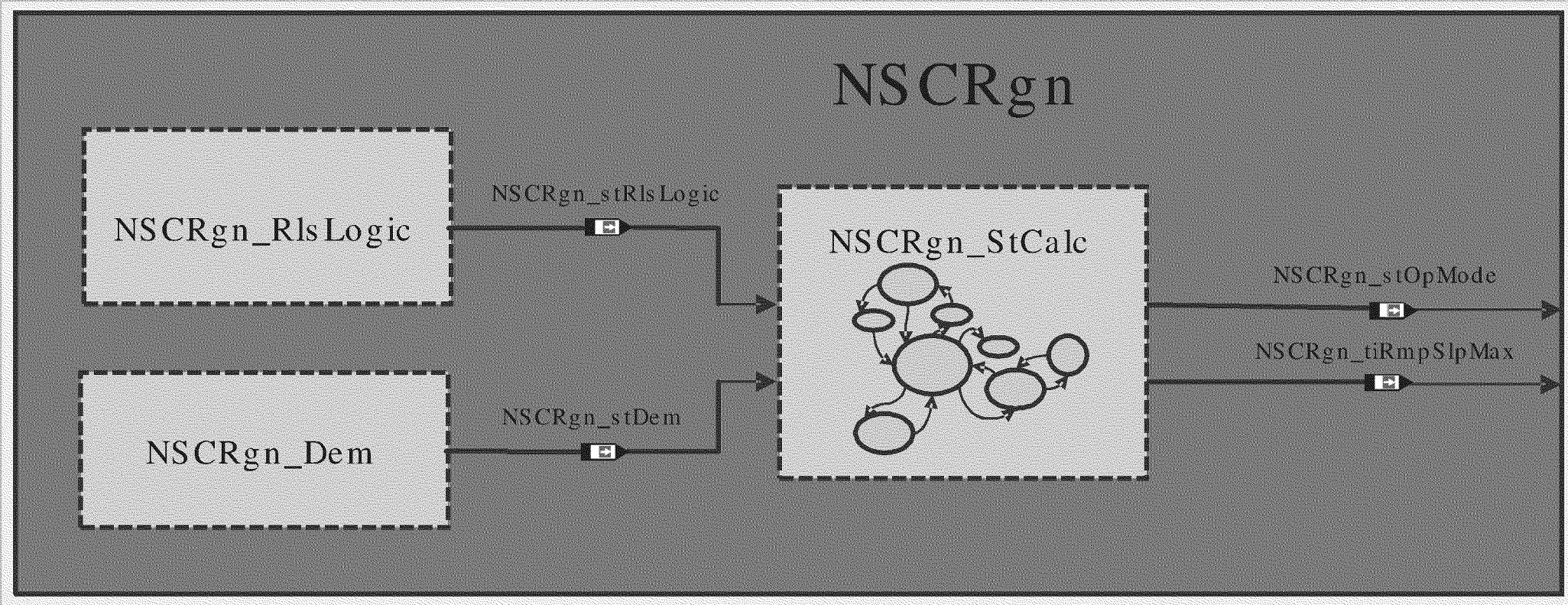
As-Calibrated vs As-Designed

- ❖ Acoustic condition used to detect emissions test cycles
 - Calibrated time-distance curves are the “smoking gun”
- ❖ *Could Bosch have designed it for a legitimate purpose?*
 - No legitimate reason for those dependencies
- ❖ What about without the time-distance curves?
- ❖ Without deactivating conditions?

Fiat 500X

- ❖ February 9, 2016: Deutsche Umwelthilfe reports testing showing Fiat 500X exceeds NOx emissions in road tests
- ❖ Fiat denies allegations

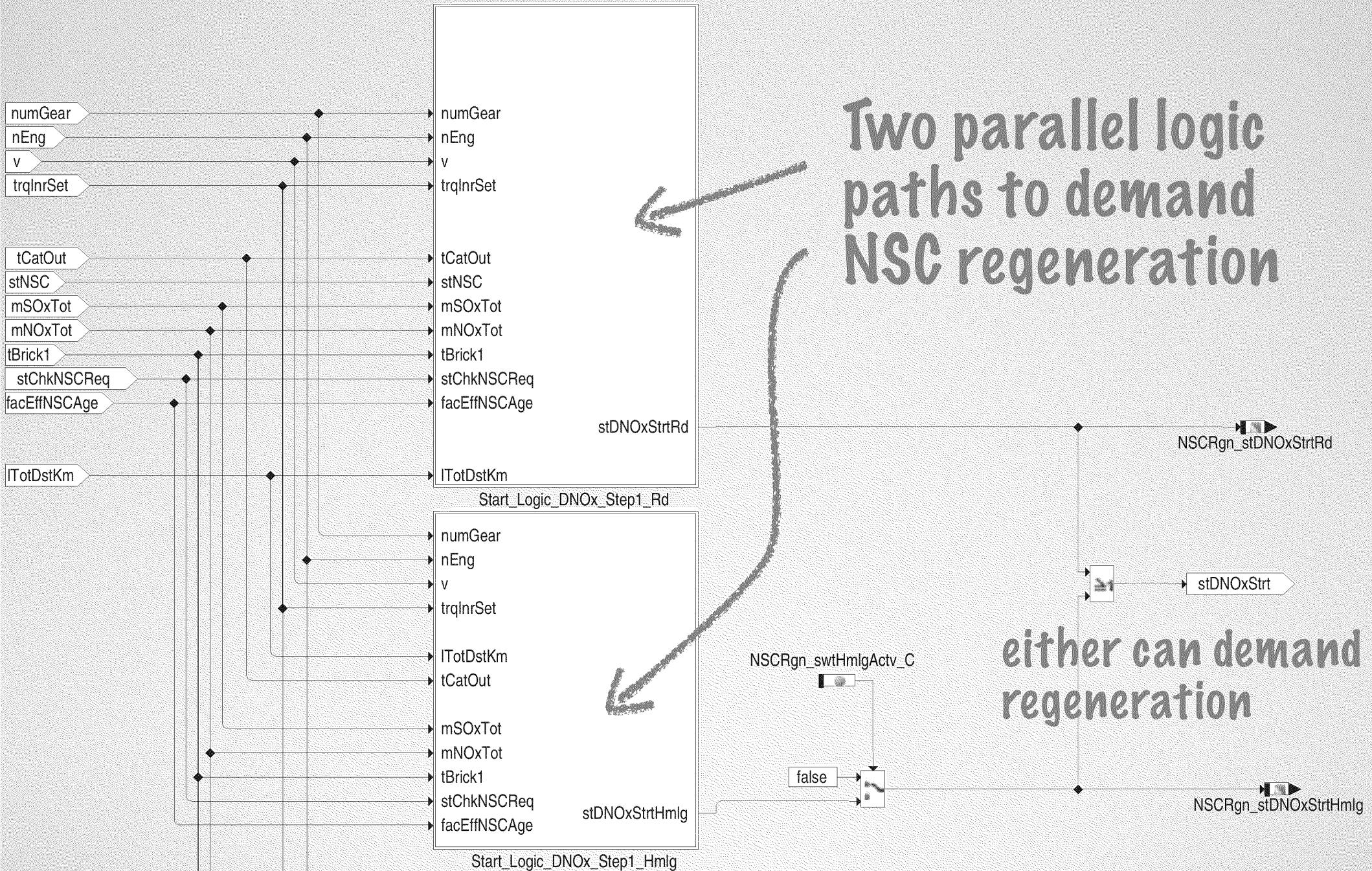
NSC Regeneration



(source: EDC17C69 P1264 function sheet © Robert Bosch GmbH, dated 2013-10-21)

ED_006561C_00000022-00053

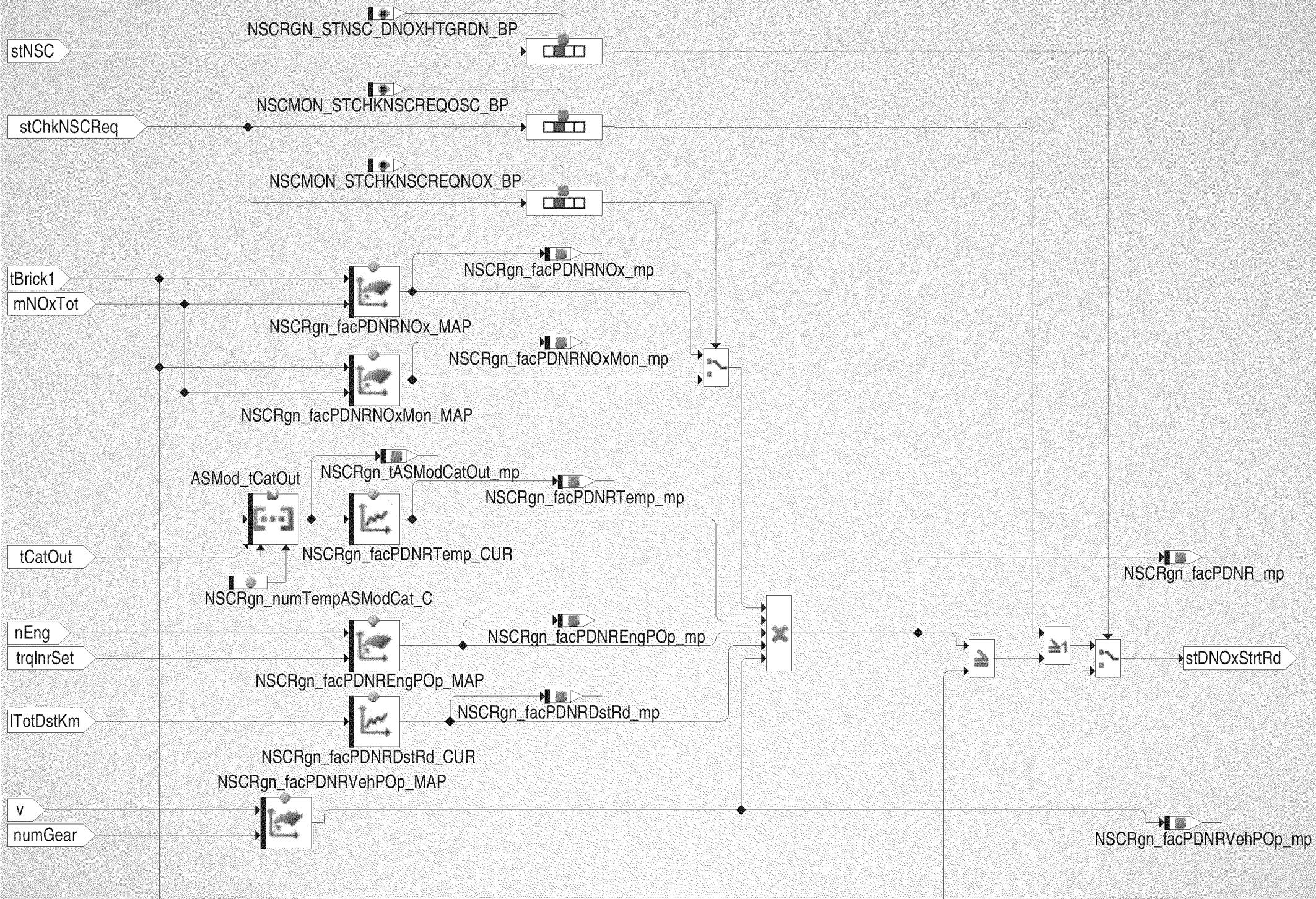
Figure 5380 Block "Start/StopLogic DNOx" [NSCRgn_Dem.NSCRgn_Dem.Start_Stop_Logic_DNOx]



(source: EDC17C69 P1264 function sheet © Robert Bosch GmbH, dated 2013-10-21)

ED_006561C_00000022-00054

Figure 5381 Block "Start Logic DNOx Step1 Real Drive" [NSCRgn_Dem.NSCRgn_Dem.Start_Stop_Logic_DNOx.Start_Logic_DNOx_Step1_Rd]



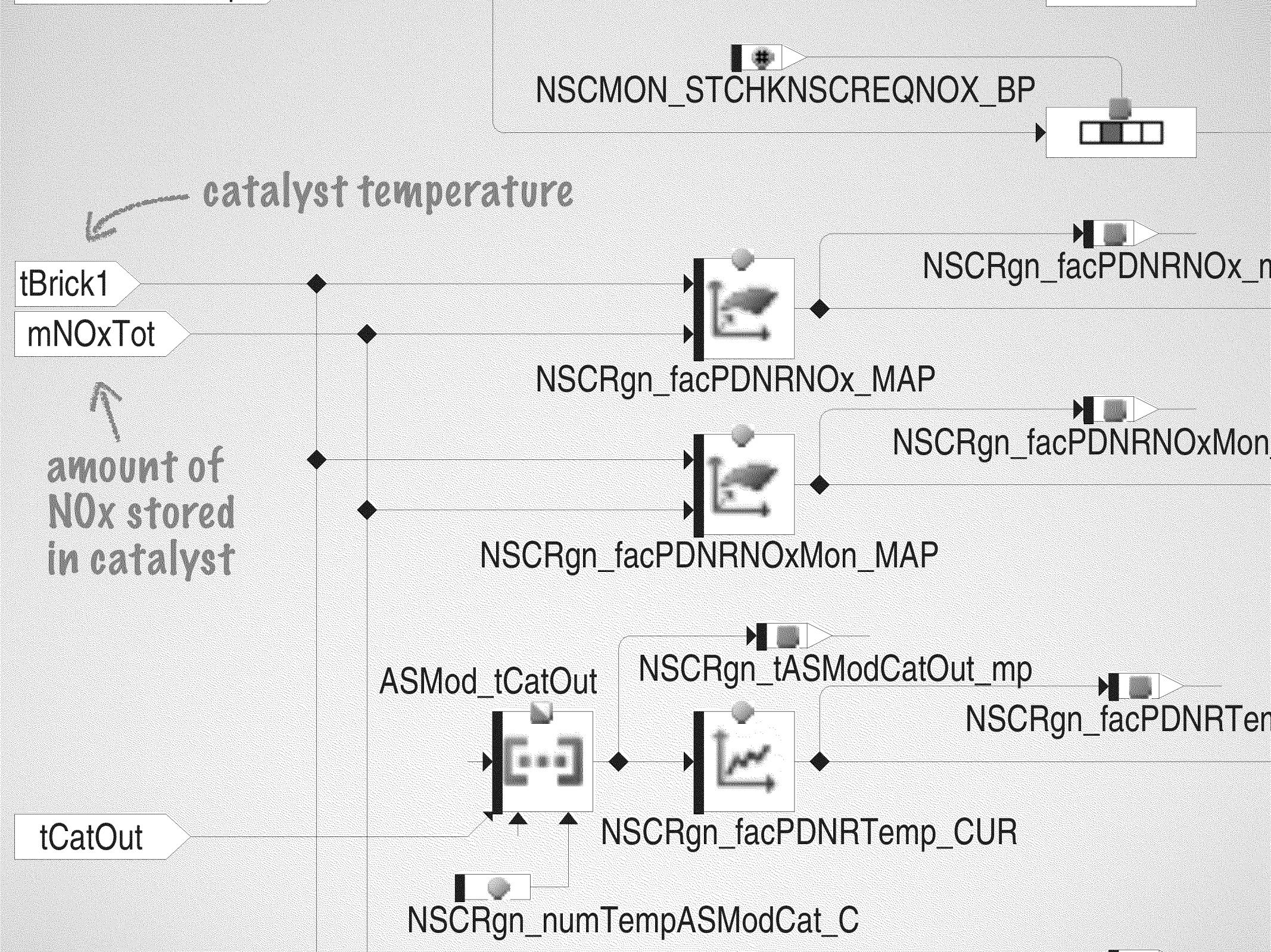


Figure 5381 Block "Start Logic DNOx Step1 Real Drive" [NSCRgn_Dem.NSCRgn_Dem.Start_Stop_Logic_DNOx.Start_Logic_DNOx_Step1_Rd]



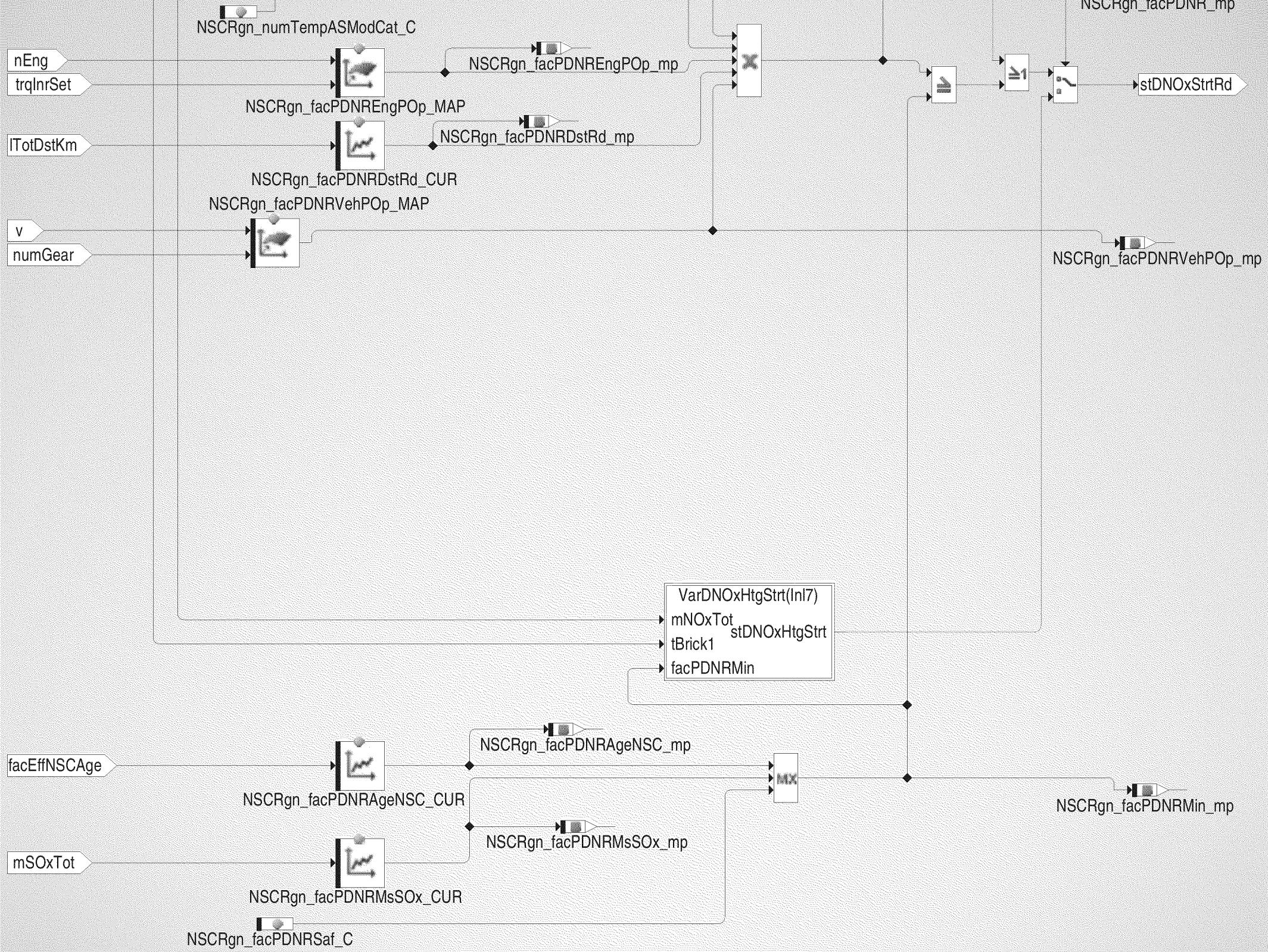




Figure 5381 Block "Start Logic DNOx Step1 Real Drive" [NSCRgn_Dem.NSCRgn_Dem.Start_Stop_Logic_DNOx.Start_Logic_DNOx_Step1_Rd]

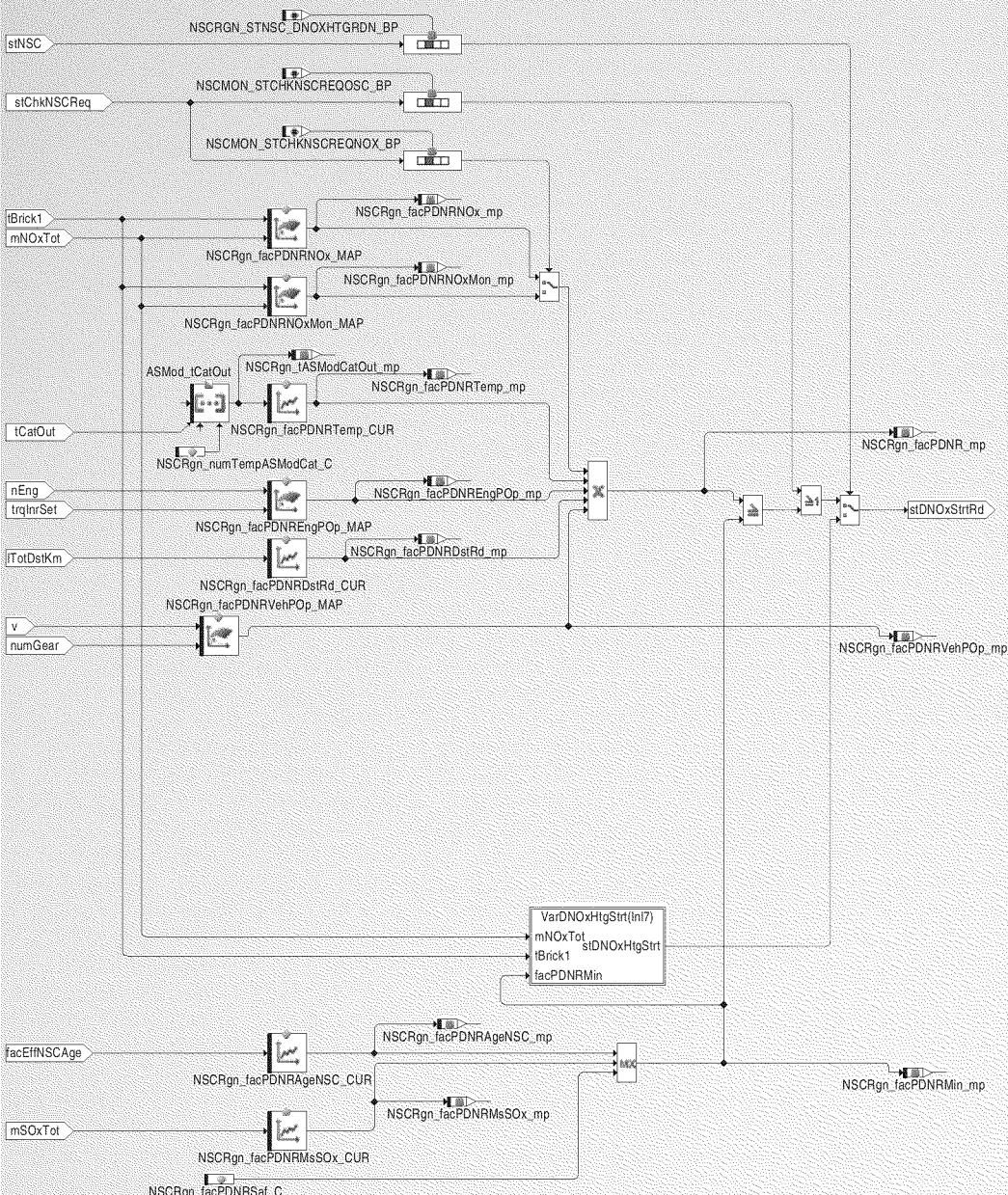


Figure 5382 Block "Start Logic DNOx Step1 Homologation" [NSCRgn_Dem.NSCRgn_Dem.Start_Stop_Logic_DNOx.Sta]

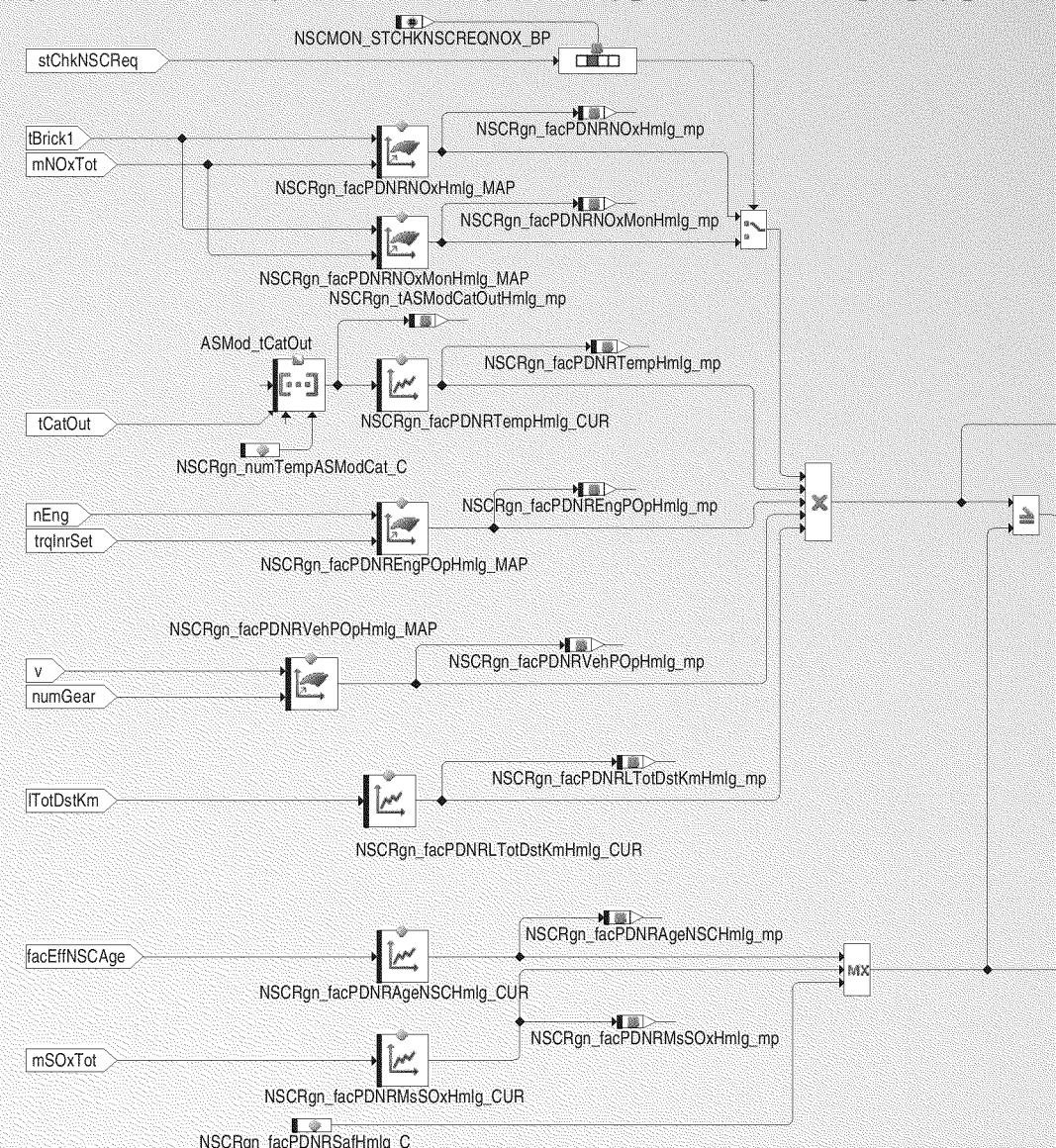


Figure 5381 Block "Start Logic DNOx Step1 Real Drive" [NSC]

Figure 5382 Block "Start Logic DNOx Step1 Real Drive" [NSC]

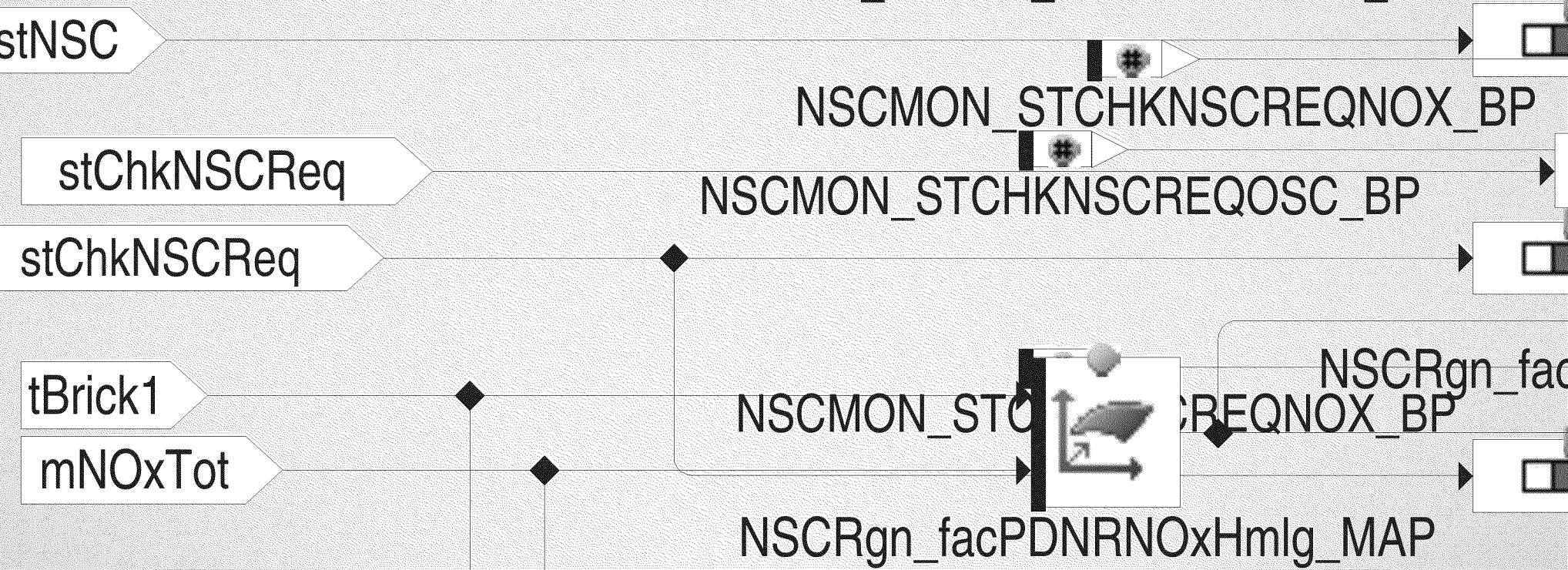


Figure 5381 Block "Start Logic DNOx Step1 Real Drive"

Figure 5382 Block "Start Logic DNOx Step1 Homologation"



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About 33,200 results (0.40 seconds)

ho·mol·o·gate

/hō' mäləgāt, hə' mälə, gāt/ ⓘ

verb

past tense: homologated; past participle: homologated

1. approve (a car, boat, or engine) for sale in a particular market or use in a particular class of racing.
2. *formal*
express agreement with or approval of.
"one body of patrons elected the teacher, the others afterward homologating the appointment"



Translations, word origin, and more definitions

Feedback

Homologate | Definition of Homologate by Merriam-Webster

<https://www.merriam-webster.com/dictionary/homologate> ▾

transitive verb. : sanction, allow; especially : to approve or confirm officially.

Homologation - Wikipedia

<https://en.wikipedia.org/wiki/Homologation> ▾

Homologation (Greek *homologeo*, ὁμολογέω, "to agree") is the granting of approval by an official authority. ... Certification is another possible synonym, while to homologate is the infinitive verb form. Sport · Motorsports

Figure 538:
Figure 5382



- ❖ Two par...
- ❖ Either or

land
Real Drive"
Homologation"
eneration
k ... ?

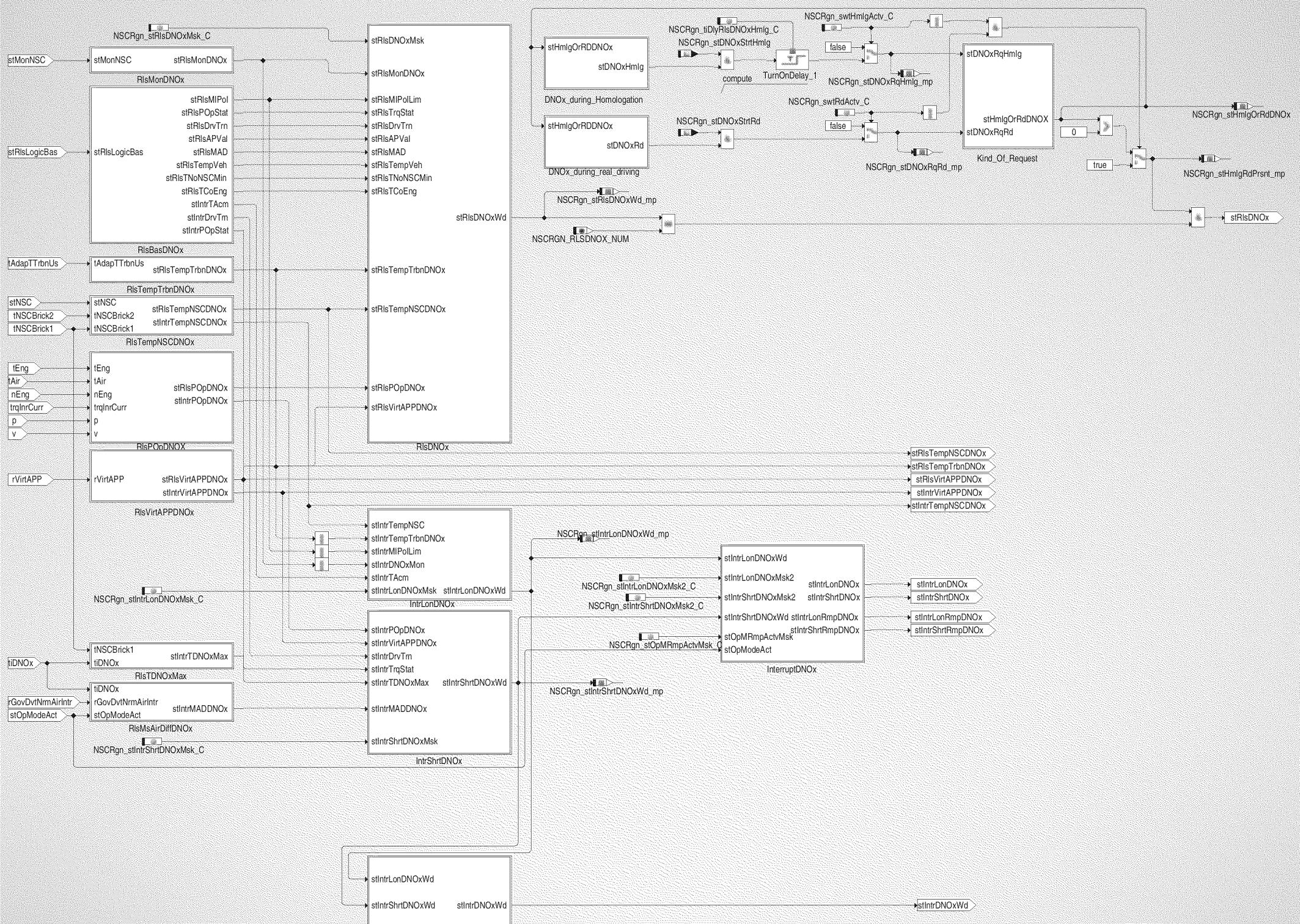
Figure 5436 Generation of the release and abort conditions for the DeNOx regeneration - block "Release Logic DNOx" [NSCRgn_RlsLogic.NSCRgnRlsLogic.RegenerationReleaseLogic.ReleaseLogicDNOx]



NSCRgn_stHmlgRdPrsnt_mp

stRlsDNOx

Figure 5436 Generation of the release and abort conditions for the DeNOx regeneration - block "Release Logic DNOx" [NSCRgn_RlsLogic.NSCRgnRlsLogic.RegenerationReleaseLogic.ReleaseLogicDNOx]



stHmlgOrRDDNOx

stDNOxHmlg

DNOx_during_Homologation

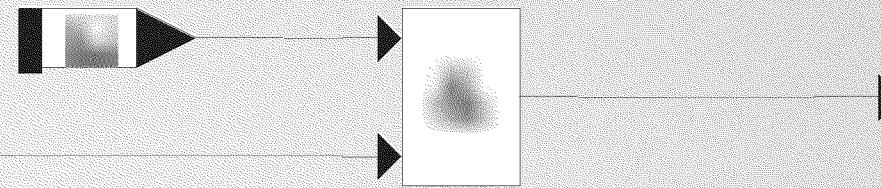
stHmlgOrRDDNOx

stDNOxRd

DNOx_during_real_driving

NSCRgn_tIDlyRlsDNOxHmlg_

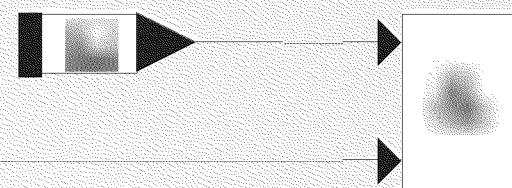
NSCRgn_stDNOxStrtHmlg



compute

Tur

NSCRgn_stDNOxStrtRd



regeneration demanded by “homologation” logic

→ stHmlgOrRDDNOx

stDNOxHmlg

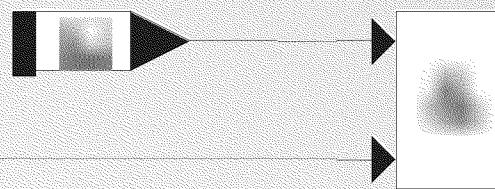
DNOx_during_Homologation

→ stHmlgOrRDDNOx

stDNOxRd

DNOx_during_real_driving

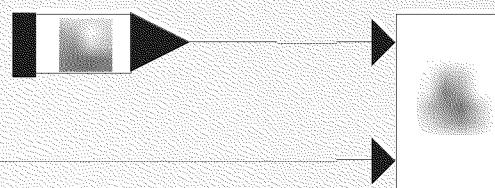
NSCRgn_stDNOxStrtHmlg



compute Tu

AND

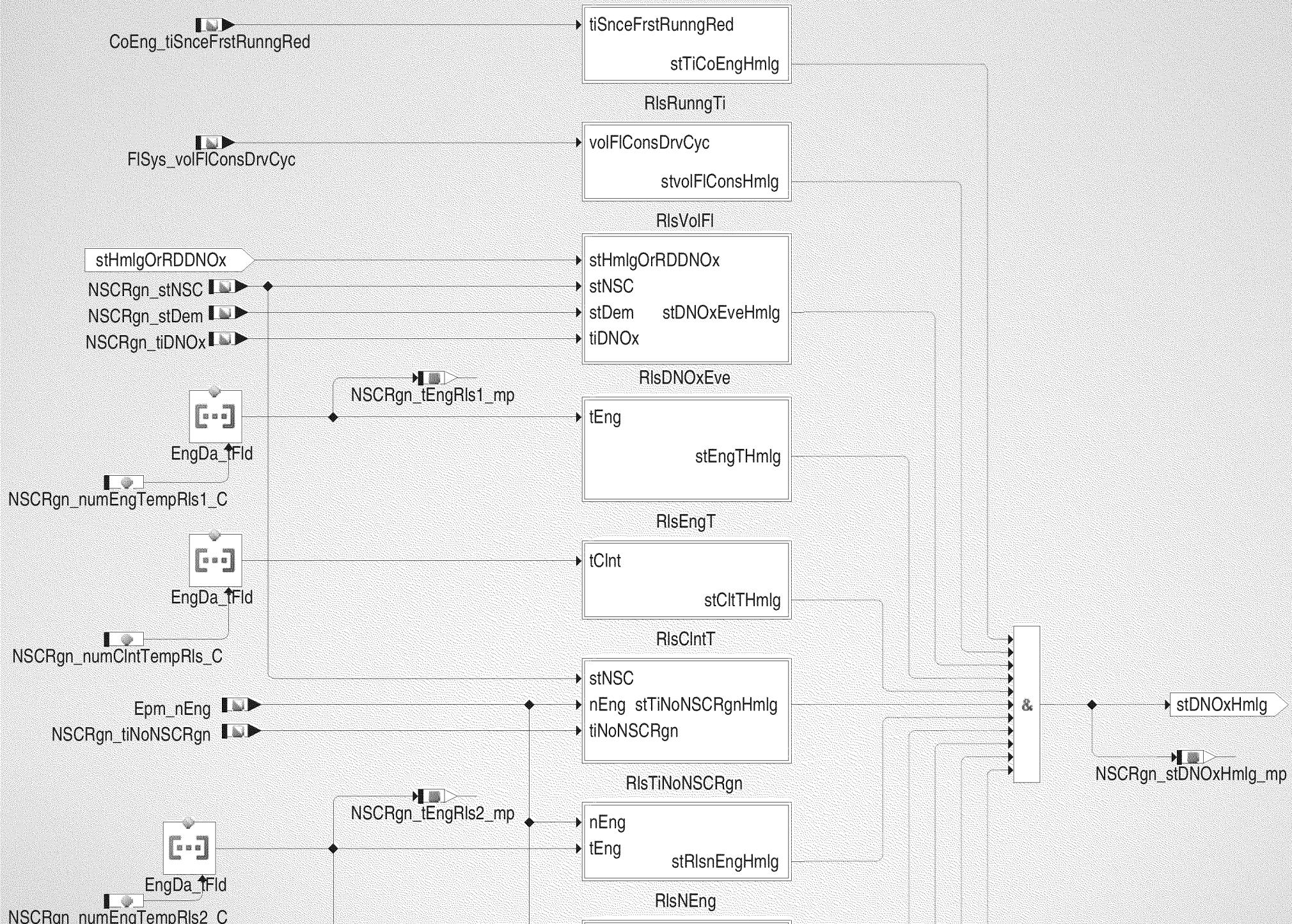
NSCRgn_stDNOxStrtRd

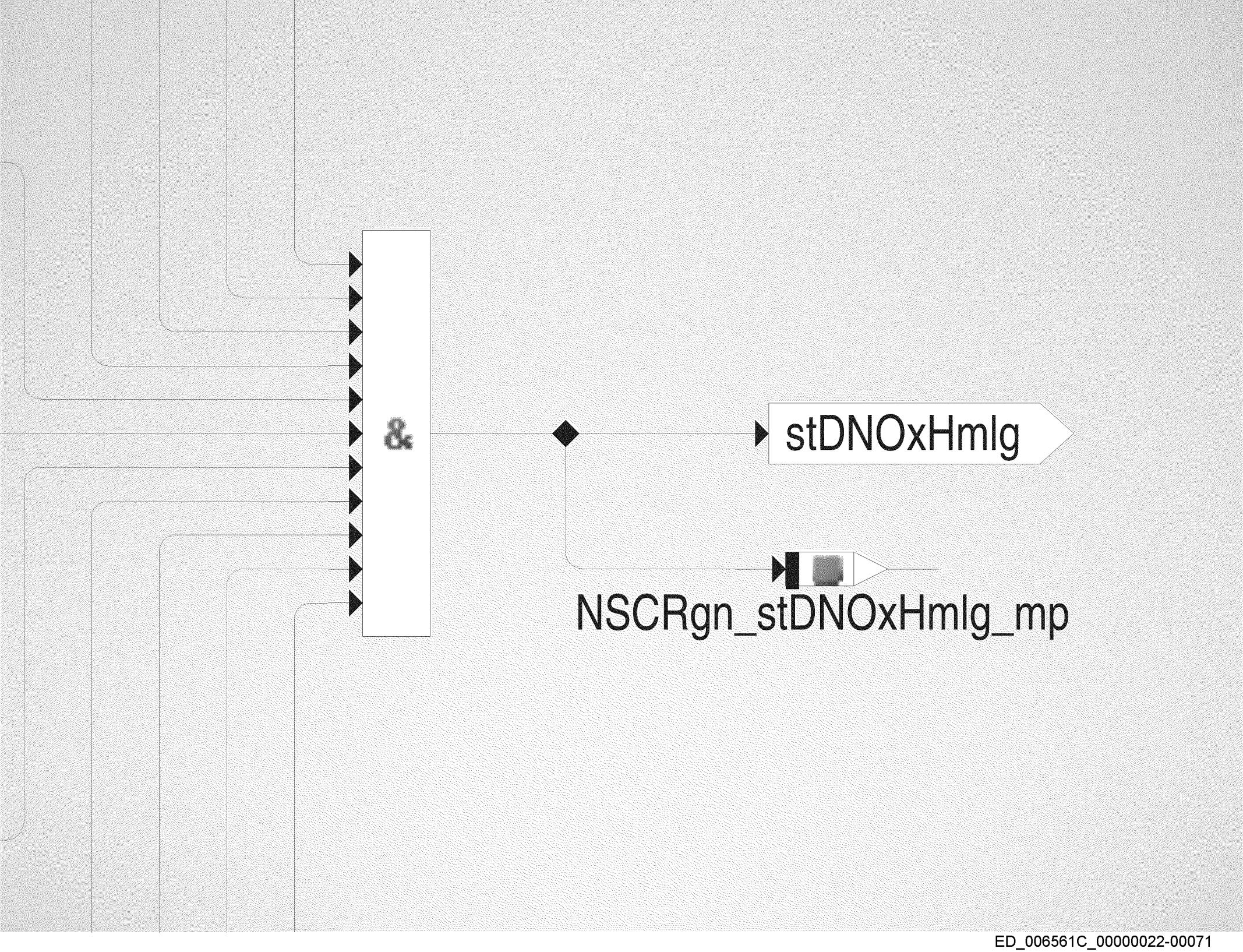


regeneration demanded
by “read driving” logic

Activation conditions to trigger the DeNOx event during homologation cycle

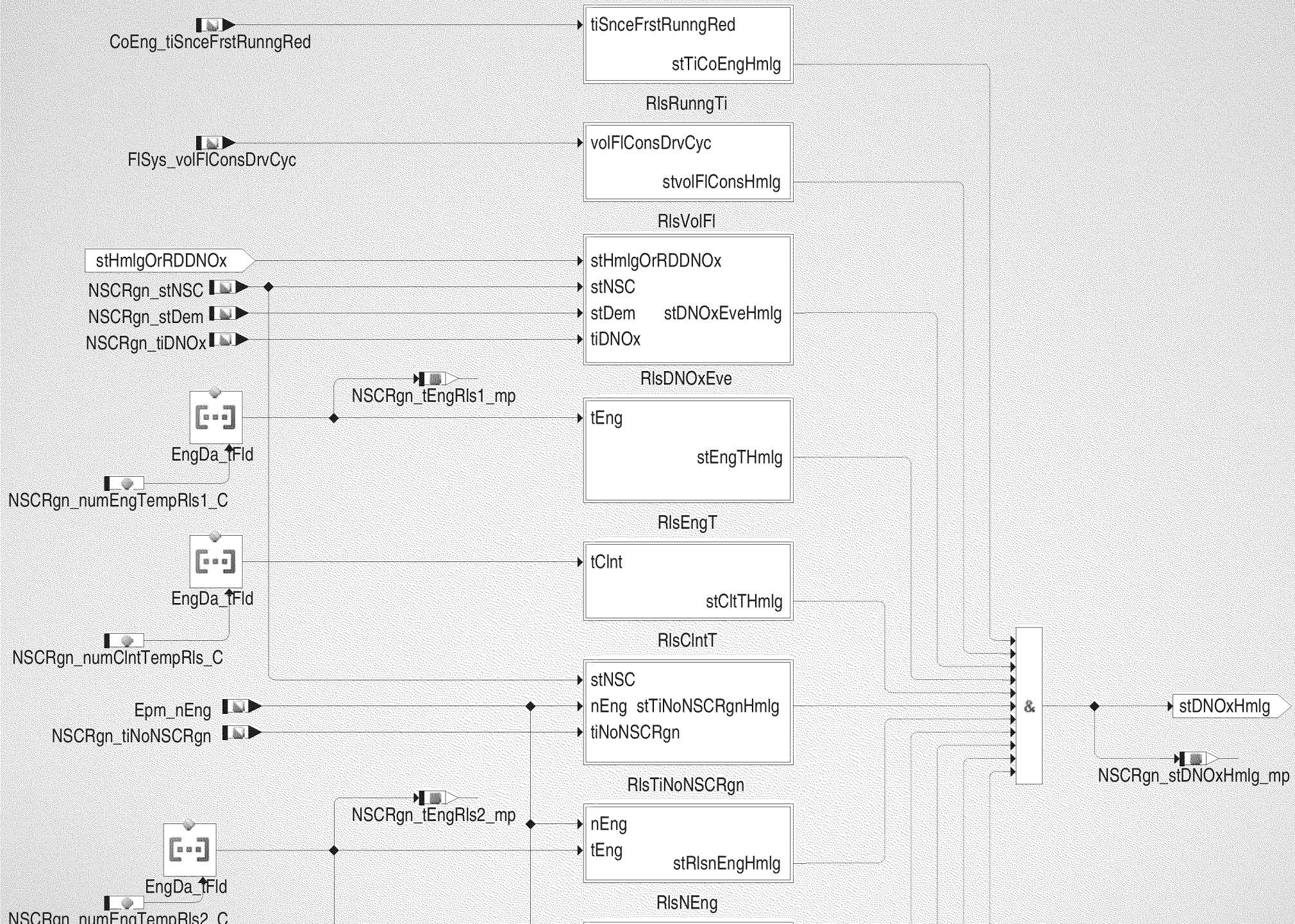
Figure 5444 NSCRgn_RlsLogic/NSCRgnRlsLogic/RegenerationReleaseLogic/ReleaseLogicDNOx/DNOx_during_Homologation [NSCRgn_RlsLogic.NSCRgnRlsLogic.RegenerationReleaseLogic.ReleaseLogicDNOx.DNOx_during_Homologation]





Activation conditions to trigger the DeNOx event during homologation cycle

Figure 5444 NSCRgn_RlsLogic/NSCRgnRlsLogic/RegenerationReleaseLogic/ReleaseLogicDNOx/DNOx_during_Homologation [NSCRgn_RlsLogic.NSCRgnRlsLogic.RegenerationReleaseLogic.ReleaseLogicDNOx.DNOx_during_Homologation]



enerationReleaseLogic/ReleaseLogicDNOx/DNO
aseLogicDNOx.DNOx_during_Homologation]

tiSinceFirstRunningRed

startTimestamp

RunningTime

volFIConsDrvCyc

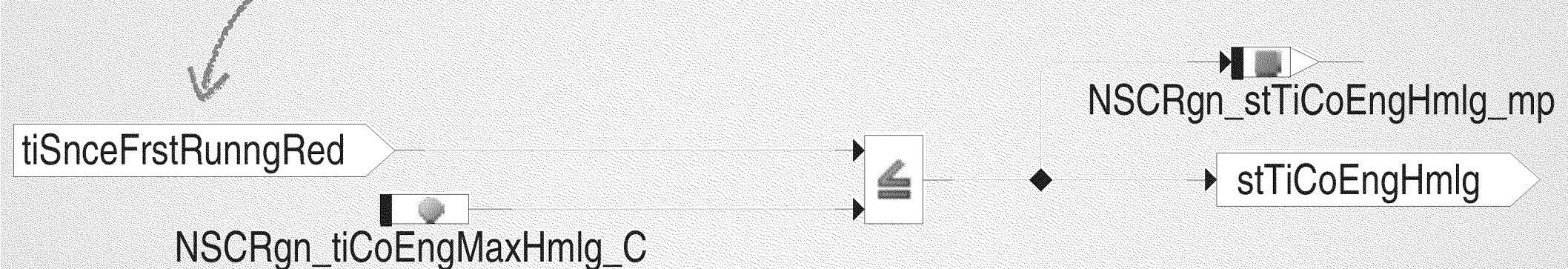
startVolFIConsTimestamp

RunningVolFI

tiSnceFrstRunngRed

stTiCoEngHmlg

time since engine start (in seconds)





- ❖ Homologation release will only happen in the first `NSCRgn_tiCoEngMaxHmlg_C` seconds of driving
- ❖ In firmware image we examined:
 $NSCRgn_tiCoEngMaxHmlg_C = 1600$ seconds
- ❖ Emissions tests are 1800 – 1900 seconds



- ❖ Fuel consumed in driving cycle so far must be less than `NSCRgn_volFIConsMaxHmlg_C` liters
- ❖ In firmware image we examined:

$$\text{NSCRgn_volFIConsMaxHmlg_C} = 1.3 \text{ liters}$$
- ❖ At 5.5 liters per 100km, 1.3 liters last 24 km
- ❖ Emissions tests are around 20 km

Fiat 500X Summary

- ❖ Two parallel sets of condition to trigger NSC regeneration: “homologation” and “real driving”
- ❖ “Homologation” conditions only active first 1600 sec
- ❖ “Homologation” and “real driving” from Bosch documentation of EDC17C69 ECU
 - Bosch knew what they were doing
- ❖ Documented purpose was to alter behavior during test

Detecting Test?

NYSE ↑ 12.05 \$ 0.00% BORSA ITALIANA ↓ 10.4 € -0.38%



FIAT CHRYSLER AUTOMOBILES



FCA on Real Driving Emissions



In the past several months the issue of diesel emissions has been the subject of a great deal of attention, particularly in Europe, where diesel is quite common.

In response to these events, FCA has conducted a thorough internal review of the application of this technology in its vehicles and has confirmed that its diesel engine applications comply with applicable emissions regulations.

In particular:



In the past several months the issue of diesel emissions has been the subject of a great deal of attention, particularly in Europe, where diesel is quite common.

In response to these events, FCA has conducted a thorough internal review of the application of this technology in its vehicles and has confirmed that its diesel engine applications comply with applicable emissions regulations.

In particular:

- FCA diesel vehicles do not have a mechanism to either detect that they are undergoing a bench test in a laboratory or to activate a function to operate emission controls only under laboratory testing. In other words, although emission levels vary depending on driving conditions, the emission control systems of the FCA vehicles operate in the same way under the same conditions, whether the vehicle is in a laboratory or on the road.
- FCA diesel vehicles when tested following the only testing cycle prescribed by European law (NEDC) perform within the regulatory limits and comply with the relevant regulatory requirements.

FCA acknowledges that public attention is shifting towards measuring emissions performances under conditions that more closely reflect real-world driving conditions, and is debating the choice of an alternative to NEDC.

Currently in Europe vehicles are being tested by a range of entities in a variety of member states

Detecting Test?

- ❖ Is Fiat 500X ECU detecting the test?
- ❖ ECU alters emissions behavior in response to conditions not encountered during emissions testing
 - Volume consumed exceeds NSCRgn_vo1FlConsMaxHmlg_C
 - Running time exceeds NSCRgn_t1CoEngMaxHmlg_C

A Software Silver Bullet?

- ❖ ***Can we detect defeat devices automatically?***
- ❖ **Yes:** If we know what they are
 - We built a tool to find the VW acoustic condition in firmware
- ❖ **No:** Probably not in general case
 - Too easy to hide an indirect dependence
 - Still need to understand what the code means

A Software Silver Bullet?

- ❖ ***Can a manufacturer formally prove that an ECU does not cheat on emissions?***
- ❖ Need to trust that inputs (sensors) and (outputs) actuators are defined honestly
- ❖ Need to trust that code on the ECU is the code that has been verified
- ❖ Producing formal proof is costly
 - Cyber-physical system verification still in its infancy
- ❖ Huge regulator burden

Lifetime Emissions Monitoring

- ❖ *Monitor each vehicle's actual emissions over its lifetime*
- ❖ No emissions testing for compliance—no defeat devices
- ❖ **Option 1 (Trust but Verify):** Verify manufacturer's emissions claim using actual data over vehicle lifetime
- ❖ **Option 2 (Cap and Trade):** Manufacturers pay fine/offset for actual emissions produced by their vehicles
- ❖ **Option 3 (Internalizing Externalities):** Consumer pays for his/her own emissions (e.g. during vehicle registration renewal).

Lifetime Emissions Monitoring

- ❖ ECU calculates cumulative lifetime vehicle emissions
 - **Verified sensors:** Broadcast sensor input on CAN bus
 - Transmitter (ECU) can't tell if anyone is listening to broadcasts
 - Anyone (e.g. CARB, EPA, independent researchers) can verify sensor accuracy
 - **Verified model update:** Broadcast computation on CAN bus
 - Transmitter (ECU) can't tell if anyone is listening to broadcasts
 - Anyone can verify model updated correctly (model must be public)
- ❖ *Research challenge:* Even a *single* bad model update must be detectable with high probability
- ❖ *Research challenge:* Need to protect consumer privacy

Conclusion

- ❖ Volkswagen defeat device
 - Acoustic function precisely detected of test conditions
 - Outcome used to alter behavior of multiple systems
- ❖ Fiat 500X defeat device
 - Parallel logic paths for triggering NSC regeneration
 - Software documentation shows Bosch complicit
- ❖ Lifetime emissions monitoring
 - New regulatory regimes
 - New technical challenges